

**RESISTANCE TO ONION THRIPS (*Thrips tabaci* Lindeman) AND
INCIDENCE OF *Iris yellow spot virus* IN ONIONS**

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RESISTANCE TO ONION THRIPS (*Thrips tabaci* Lindeman) AND INCIDENCE OF *Iris yellow spot virus* IN ONIONS

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Onion thrips, *Thrips tabaci* Lindeman, a worldwide pest of onion, *Allium cepa* L., can reduce onion yield by >50% and transmit *Iris yellow spot virus* (IYSV), confirmed in 2006 in New York. *T. tabaci* are difficult to control with conventional insecticides and have developed resistance to some insecticides in New York. For these reasons, it is necessary to develop a research program aimed at finding alternative management strategies for *T. tabaci* and IYSV. In field studies over a 2-year period, 49 onion cultivars were screened and 11 had very little leaf damage and were considered resistant to *T. tabaci*. Choice and no-choice tests were performed to characterize resistance of different cultivars to *T. tabaci*. Resistant cultivars showed an intermediate to high antibiotic effect to *T. tabaci* and a very strong antixenotic effect. A study on behavioral responses of walking *T. tabaci* adults using a Y-tube olfactometer suggested that there is not an oriented movement towards onion plant odors. To detect the presence of IYSV transmitted by *T. tabaci*, in a laboratory experiment, onion cultivars were infested with *T. tabaci* larvae from an IYSV-infected onion field. In a complementary experiment, plants were moved to an infected IYSV-field. All the cultivars became infected with IYSV. The infection varied from 3 to 25% and 37 to 70% in the laboratory and field experiments, respectively. It was observed that cultivars that were identified as resistant to *T. tabaci* were not

necessarily resistant free of the virus and vice versa. Visual assessment indicated that all resistant cultivars had yellow-green colored foliage, whereas susceptible ones had blue-green colored foliage. The reflectance spectrum was measured on leaves using a spectrometer in order to determine if light reflectance was associated with resistance to *T. tabaci*. Susceptible cultivars had the highest values of leaf reflectance in the first (275-375 nm) and second (310-410 nm) theoretical photopigment-system of *T. tabaci* and these values were significantly different from most resistant cultivars. These results indicated a strong response of *T. tabaci* to onion cultivars with higher reflectance in the UV range (270-400).

BIOGRAPHICAL SKETCH

John Diaz-Montano was born in the city of Palmira, Colombia. After graduating from high school, he enrolled the National University of Colombia in Palmira where he obtained a B.S. in Agronomical Engineering in 2001. In 2003 he moved to Manhattan, Kansas where he attended Kansas State University to get his Master's degree in Entomology. In 2006, he started a Ph.D. program also in Entomology at Cornell University. In 2010 he moved to California where he is currently a postdoctoral scholar at the University of California in Riverside.

I dedicate this dissertation to my mother, my siblings, all other family members for their love and support at the distance and Catalina M.

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CHAPTER 1

Onion Thrips (Thysanoptera: Thripidae): A Global Pest of Increasing Concern in Onion¹

Abstract

Over the last two decades, onion thrips, *Thrips tabaci* Lindeman, has become a global pest of increasing concern in onion, *Allium cepa* L., because of its development of resistance to insecticides, ability to transmit plant pathogens and frequency of producing more generations at high temperatures. *Thrips tabaci* feeds directly on leaves causing blotches and premature senescence as well as distorted and undersized bulbs. *Thrips tabaci* can cause yield loss greater than 50% but can be even more problematic when it transmits *Iris yellow spot virus* (IYSV). IYSV was identified in 1981 in Brazil and has spread to many important onion-producing regions of the world, including several states in the USA. IYSV symptoms include straw-colored, dry, tan, spindle- or diamond-shaped lesions on the leaves and scapes of onion plants and can cause yield loss up to 100%. In this paper, we review the biology and ecology of *T. tabaci* and discuss current management strategies based on chemical, biological and cultural control as well as host resistance. Future directions for research in integrated pest management are examined and discussed.

¹ Diaz-Montano, J., M. Fuchs, B. A. Nault, J. Fail and A. M. Shelton. Onion Thrips (Thysanoptera: Thripidae): A Global Pest of Increasing Concern in Onion. J. Econ. Entomol. Submitted on July-16-2010.

Resumen (Spanish)

En las ultimas dos décadas, el trips de la cebolla, *Thrips tabaci* Lindeman, se ha convertido en una plaga mundial de alto interés en cebolla, *Allium cepa* L., debido a su desarrollo de resistencia a insecticidas, capacidad para transmitir patógenos en plantas y producción de mayor numero de generaciones a altas temperaturas. *Thrips tabaci* se alimenta directamente sobre las hojas causando manchas, senescencia prematura, así como bulbos pequeños y desformados. *Thrips tabaci* puede causar perdidas en rendimiento mayores al 50%, pero esta plaga puede ser aun más problemática cuando transmite *Iris yellow spot virus* (IYSV). IYSV fue identificado en Brasil en 1981 y desde entonces se ha propagado a importantes regiones productoras de cebolla a nivel mundial, incluyendo diferentes estados en los Estados Unidos. Los síntomas del IYSV incluye lesiones secas en forma angular o de diamante, de color café claro en las hojas y tallos de la cebolla y puede producir hasta 100% de perdidas en rendimiento. En este articulo nosotros revisamos la biología y ecología de *T. tabaci* y presentamos los actuales métodos de manejo basados en control químico, biológico y cultural así como el método de resistencia de plantas a insectos. Las direcciones futuras para investigación en manejo integrado de esta plaga son analizadas.

Introduction

Onion thrips, *Thrips tabaci* Lindeman, has been the subject of considerable research and extension publications since it was first described in 1888 (Lindeman 1889). Some aspects of its biology, ecology and management have been summarized in T. Lewis' highly regarded 1997 book "Thrips as Crop Pests," but a considerable amount of detail important for its management on onion (*Allium cepa* L.) was not included or has

developed since its publication. For example, in many parts of the world *Iris yellow spot virus* (family *Bunyaviridae*, genus *Tospovirus*, IYSV), which infects onion and is only transmitted by *T. tabaci*, has caused serious losses in several countries but is not mentioned in the book. Furthermore, management of *T. tabaci* specifically on onion was not emphasized in the book, but onion is a major vegetable crop that was harvested on 198,913 ha (green onions) and 3,731,659 ha (dry onions) worldwide in 2008 (FAO 2009) and *T. tabaci* is an increasingly difficult pest to control on this crop. Our purpose in this review is to highlight important aspects of the history, biology, ecology and management of *T. tabaci* as it pertains to onion and to stimulate discussion for future work on this important global pest of onion.

Taxonomy, Origin, Host Range and Geographic Distribution of *T. tabaci*

Thrips tabaci was first described by a Russian entomologist, Karl Eduard Lindeman, based on specimens collected in Bessarabia, Russia that caused severe damage to tobacco plants (Lindeman 1889). *Thrips tabaci* belongs to the order Thysanoptera, suborder Terebrantia, family Thripidae and subfamily Thripinae (Mound and Walker 1982). *Thrips tabaci* is believed to be a native of the eastern Mediterranean (Mound and Walker 1982, Mound 1997), which is the center of origin for its most important host plant, i.e. onion (Mound 1997). *Thrips tabaci* has a wide host range compared with other thrips species. Some reports list *T. tabaci* on 141 plant species in 41 families (Ghabn 1948), while others list it on more than 355 species of flowering plants (Morison 1957), and still others list it on 140 plant species within 40 families (Ananthakrishnan 1973). Despite its large host range, onion is a favorite host and is one of the few crops attacked by the same species in different parts of the world (Lewis 1973, 1997b). *Thrips tabaci* is a cosmopolitan pest of onion grown between sea level and 2000 m (Lewis 1973, 1997b). It is present in Europe, North America,

South America, Africa, Asia and Australia (Mound 1997). In the second half of the 19th century several authors reported a thrips species called “onion thrips” causing damage to onion crops in the USA and in the Bermuda Islands, but the species was either misidentified (Packard 1872, Gillette 1893, Osborn and Mally 1895) or not identified at all (Shipley 1887, Thaxter 1890). Theodore Pergande, an American entomologist, after carefully examining and comparing the *T. tabaci* specimens sent to him by Karl E. Lindeman with the specimens of the so called “onion thrips”, collected from onion and several other host plants in the USA, confirmed that they were in fact the same species (Pergande 1895). Since then, the thrips species reported causing damage on onion (Slingerland 1896, Webster 1901, Chittenden 1913) has been called onion thrips in the English literature. Despite the fact that the first description of *T. tabaci* was published in Europe in 1889, the species had been collected between 1882 and 1888 on onion; cabbage (*Brassica oleracea* L.), cucumber (*Cucumis sativus* L.) and parsley (*Petroselinum crispum* L.), and then identified correctly by Pergande in North America for the first time in the early 1890s (Pergande 1895). *Thrips tabaci* spread subsequently throughout the United States and southern Canada by the early 1900s (Capinera 2001). *Thrips tabaci* is considered a pest of significant economic importance on different plant species during dry weather in temperate and subtropical regions (Morison 1957).

Morphology, Development and Reproduction of *T. tabaci*

Thrips tabaci adults vary in color from pale yellow to dark brown (Morison 1957, Mound 1967, Nakahara 1991, Triplehorn and Johnson 2005) depending on temperature during their development (Sakimura 1937, Murai and Toda 2001). Adult *T. tabaci* that develop faster during the summer or at high temperatures are usually smaller and paler than those that develop slowly during winter or lower temperatures

(Mound 1997). *Thrips tabaci* females vary in size and color from small pale to large dark, probably in response to temperature during development (Mound 1973), males are smaller and paler than females (Morison 1957). Murai and Toda (2001) demonstrated that *T. tabaci* adult body color and size are determined by temperature during the pupal and larval stages, respectively. Generally, adult females are 1.0 to 1.3 mm in length, and males about 0.7 mm in length (Pergande 1895).

As with all Terebrantia, the life cycle of *T. tabaci* consists of an egg, first and second larval instars, pre-pupa, pupa and adult (Ghabn 1948, Nakahara 1991). Another stage of *T. tabaci* was described by Gawaad and El-Shazli (1970) as the “prenymph”, which is an apodous larva with a developed head and two red eyes that has not completely escaped from the egg pocket. Eggs are kidney shaped and are inserted either in the upper or lower surface of a leaf very close to the surface and always inserted diagonally at approximately 60° (Gawaad and El-Shazli 1970). Eggs are ca. 0.26 mm in length (Ghabn 1948).

It is difficult to identify *T. tabaci* larvae from other thrips species. In Egypt, Ghabn (1948) compared *T. tabaci* to other thrips species and observed that larvae of *T. tabaci* have the shortest macrosetae (lateral bristles of the prothorax), about 20 µm. Also, the larvae do not have the dark gray chitinous markings on the dorsum of the thorax, which is present in many other thrips species. The tiny elements of the sculpture of the abdomen consist of pointed small protuberances while in other thrips species these elements are larger and rounded. In general, larvae of the family Thripidae have 7-segmented antennae, three thoracic segments and a pair of spiracles on the mesothorax, and a 10-segmented abdomen with a pair of spiracles on abdominal segments II and VIII. The first instar differs from the second instar by having six pairs of setae on the pronotum and four pairs of setae on abdominal segments III-VII. The second instar has seven pairs of setae on the pronotum and six

pairs of setae on abdominal segments III-VII (Nakahara 1991). The short third antennal joint and the pointed terminal joint distinguish the first instar of *T. tabaci*, while the antenna of the second instar is more slender and the terminal joint is rounded at the tip. Recently, a comprehensive identification key to the second instar larvae of 130 species of Thripidae, including *T. tabaci*, has been published by Vierbergen et al. (2010).

The prepupa and pupa of *T. tabaci* differ from the larvae by the presence of wing sheaths (Ghabn 1948). The prepupa and pupa of *T. tabaci* can be differentiated by the development and orientation of the antennae and the length of the antennae and wing sheaths (Ghabn 1948).

Adult *T. tabaci* have a gray or yellowish-gray ocellar pigment (Morison 1957, Stannard 1968), front wing with four setae (occasionally 2-6) on the distal half of first-vein (Moritz et al. 2001), seven segmented antennae (Mound and Walker 1982, Bournier 1983) with the first and the base of segments three and four lighter than the others (Stannard 1968) and do not have the accessory setae on the abdominal sternites (Bournier 1983). The grayish ocellar crescent distinguishes *T. tabaci* from most species in Thripidae, which have orange to red ocellar crescents. Other diagnostic characters are the short posteroangular setae present on the pronotum, and the posteromarginal comb on abdominal segment VIII with long, close-set teeth (Nakahara 1991, 1994), which is complete dorsally; pronotal bristles 33-45 µm long without accessory bristles on abdominal sternites (Morison 1957) and pleurotergites without discal setae but with sculpture of rows of fine microtrichia (Moritz et al. 2001).

Only a few thrips species, such as *T. tabaci*, reproduce by parthenogenesis (Moritz 1997), which is the production of offspring without fertilization by a male (Ananthakrishnan 1990). In the eastern Mediterranean and Iran, the sex ratio of *T.*

tabaci was 1:1 (Lewis 1973, Mound 1973), suggesting that the population was sexually reproducing, but in most temperate regions of the world, only parthenogenetic forms of *T. tabaci* have been reported (Lewis 1973, Kendall and Capinera 1990).

Thelytoky is the most common reproductive mode in *T. tabaci* (Lewis 1973, Kendall and Capinera 1990). Thelytoky is a type of parthenogenesis in which unfertilized eggs develop into females (Lewis 1973). *Thrips tabaci* also can reproduce by arrhenotoky (Kendall and Capinera 1990), in which unfertilized eggs develop into males and fertilized eggs into females (Lewis 1973). Deuterotoky is an uncommon parthenogenetic mode of reproduction in thrips and was reported for the first time occurring in *T. tabaci* by Nault et al. (2006). Deuterotoky occurs when unfertilized eggs develop into either males or females.

In New York, Gangloff (1999) reported for the first time the presence of male *T. tabaci* in different fields in a commercial onion-growing region (Yates County). In research conducted from 2001-2 in Canada, MacIntyre-Allen et al. (2005a) studied the sex ratio of *T. tabaci* in onion fields by using water pan and sticky traps and found that 100% of the *T. tabaci* captured were females. Additionally, *T. tabaci* populations collected from the field in 2000 and reared in laboratory conditions until 2004 did not produce males. In New York, Nault et al. (2006) sampled *T. tabaci* in 20 onion fields from six different counties and found half of the population was thelytokous with the other half being a mix of thelytokous, arrhenotokous and deuterotokous. The various reproduction systems of *T. tabaci* likely contribute to it becoming more problematic since, for example, thelytokous individuals are not dependent on finding mates and, if they are resistant to an insecticide, then their offspring will be as well.

Usually *T. tabaci* overwinter as adults (Shirck 1951, Lewis 1973, North and Shelton 1986b, Sites and Chambers 1990). Sites and Chambers (1990) found that temperature induces diapause in *T. tabaci* populations and eggs can be laid as soon as temperature increases during the spring. *Thrips tabaci* lay eggs where they feed and move continually to younger tissue (Theunissen and Legutowska 1991). *Thrips tabaci* lay more eggs and develop faster on onion leaves than on onion bulbs (Gawaad and El-Shazli 1970); however, they lay their eggs indiscriminately on leaves, cotyledons, petals, sepals and glumes (Lewis 1973). Compared to other thrips species, *T. tabaci* lay about three times more eggs during the first 10 d of oviposition than in the last 10 d (Sakimura 1937), which allows a rapid establishment of large populations.

In Table 1.1, we present a summary of different studies of *T. tabaci* development time on onion under different temperatures. The short development time and high fecundity of *T. tabaci* often results in population outbreaks.

Seasonal Patterns of *T. tabaci* on Hosts in the Onion Cropping System

Thrips tabaci infests crops that are ephemeral in the landscape. For example, onion is generally in the ground for three months before they are harvested so insects such as thrips must evolve strategies that can deal with continuously changing habitats. Understanding the factors that influence their movement patterns, especially in the varied landscapes onion is often grown in, may provide insight into enhanced management in crops such as onion.

Horsfall (1921) investigated the sources of infestation of *T. tabaci* and found that it became a problem for onion only after nearby fields of alfalfa were established for two consecutive seasons. In this study, dispersal flights were observed soon after alfalfa was cut. Similarly, North and Shelton (1986a) observed many thrips in cabbage fields only when maturation and/or mowing of other field and forage crops occurred.

Overwintering populations in field and forage crops are important sources of *T. tabaci* that infest vegetable crops (North and Shelton 1986a,b, Weiss and Beshear 1987, Chambers and Sites 1989). However, such sites are not the only source for *T. tabaci*. Larentzaki et al. (2007) found that *T. tabaci* overwinters in the soil within onion fields and surrounding vegetation and that volunteer onion plants could be important hosts for thrips before the newly planted onion crop emerges in the spring. *Thrips tabaci* also colonized volunteer onion plants left in the field in the fall, as well as weed species such as pigweed, *Amaranthus hybridis* L., lambsquarters, *Chenopodium album* L. (Larentzaki et al. 2007). *Thrips tabaci* also was found on several other weed species listed by Ghabn (1948), Morison (1957), Ananthakrishnan (1973) and Smith (2010).

Thus, it is clear that onion areas, especially those that are grown continuously to onion such as the typical muck areas in the northeastern USA, may be more of a ‘closed system’ than was previously assumed. This has important ramifications for control practices because insecticide use in an individual field may cause localized resistance, which may become a perennial problem if immigration of susceptible individuals is limited and resistance is stable. Localized patterns of resistance have been observed in the onion growing regions of NY (Shelton et al. 2003, 2006) lending evidence to the idea of a more ‘closed system’. Harding (1961) also studied the effect of migration on *T. tabaci* populations and observed minimal movements of thrips to onion crops and attributed damage to within-field movements and reproduction, rather than to migration.

Table 1.1. Development stages (days) of *Thrips tabaci* on onion

Temp (°C)	Egg	L1	L2	Prepupa	Pupa	Total	Preov	Ovip	Eggs/Fem	Ad.Long	Reference
	3.6	---	6.4---	1.2	3.2	14.4	2.8	49.6	80.1	58.2	Sakimura 1937
	5.6	---	8.6---	2.0	4.2	20.4	3.9	44.2	53.9	51.7	
15.8	8.5	---	6.5---	2.0	4.0	21.0			49.8	18.8	Lall and Singh 1968
18.0	7.9	---	6.2---	2.0	3.5	19.6			51.7	19.6	
23.4	6.0	---	5.5---	1.7	2.8	16.0			55.0	20.1	
30.8	4.8	---	5.3---	1.4	2.4	13.9			28.2	20.2	
25.0	3.4	2.4	2.8	2.2	3.1	13.9	1.4	15.6	23.6	17.8	Gawaad and El-Shazli 1971
17.5	15.1	---	-----	15.3-----	-----	30.4	5.7				Edelson and Magaro 1988
27.5	4.3	---	-----	6.8-----	-----	11.1	1.0				
23.4	4.6	2.06	4.03	1.2	2.3	14.2	4-6	15.2	40.65	21.5	Guzman et al. 1996
32.0	4.33	2.09	2.04	1.17	2.4	12.0	2.7	19.5	37.0	21.5	Salas et al. 1993
23.4	3.2	2.7	2.9	1.9	3.5	14.2	2.0	8.0	39.0	11.5	Arrieche et al. 2006

L1: 1st larval instar; L2: 2nd larval instar; Total: duration (d) from egg to adult; Preov.: Preoviposition; Ovip.: Oviposition;

Egg/Fem.: Number of eggs produced per female; Ad. Long.: Adult Longevity.

Abundance and distribution of *T. tabaci* in onion fields are affected by agricultural practices within and near onion fields. Early in the season, *T. tabaci* populations are significantly higher in onion fields initiated from transplants compared with those initiated from seed, presumably because transplanted onions are much larger and likely more attractive to thrips at the time of colonization (Hsu et al. 2010). Once an onion field is colonized, the distribution and abundance of thrips may change over time. In Texas, Edelson et al. (1986) reported that within-field populations of *T. tabaci* increased progressively through the season and the largest numbers were observed just before harvest. In New York, Shelton et al. (1987) found that the pattern of onion thrips distribution between plants was random although there were some edge effects, suggesting some movement into the field from surrounding areas. Similar edge effects in onion were found by Horsfall (1921) in Iowa and attributed to harvesting of nearby alfalfa fields. On a within-plant level, Sites et al. (1992) observed that during the onion vegetative stage, *T. tabaci* populations were concentrated on the center leaves but progressively populations became equally distributed all over the leaves. Mo et al. (2008) observed that when onion plants were young and *T. tabaci* densities were low, higher numbers of larvae than adults gathered at the base of plants. When onion plants matured and thrips densities increased, the larvae dispersed to other parts of the leaves. At all times, more adults were found in the upper than in the basal sections of the plant. Eggs were laid all over the plant, but leaves of intermediate ages had more eggs than younger and older leaves.

Environmental Effects on *T. tabaci* Outbreaks

Hot and dry weather promotes the increase of *T. tabaci* populations (Bailey 1934, Rueda et al. 2007), and severity of thrips injury (Lewis 1973). However, it is difficult to determine if the effect is nutritional or due to the reduction of mortality

from rain (Kirk 1997). It also has been suggested that water stress may increase the nutritional quality of the plant, increasing attractiveness of the plant to thrips (Lewis 1973). After heavy rains, thrips species, such as *T. tabaci*, can be washed off plants (Harris et al. 1935, North and Shelton 1986a).

The number of *T. tabaci* on onion can be enormous. Lewis (1973) estimated *T. tabaci* densities of 740 to 1600 x 10⁶ ha⁻¹ for larvae on onion in the USA. Srinivasan et al. (1981) sampled an onion field with an average of 10.9 thrips per plant, and the distribution was clumped. Edelson et al. (1986) found that when *T. tabaci* density was > 1 thrips per plant the distribution was clumped, but when it was < 1 thrips per plant, the distribution was more uniform or not significantly different from a random distribution. Shelton et al. (1987) found some “hot spots” where *T. tabaci* was concentrated along the borders in some of the six commercial onion fields sampled during the middle of the growing season but that the distribution throughout the field was essentially random.

Damage Caused by *T. tabaci* on Onion

Thrips tabaci is considered an indirect pest of dry bulb onion because it feeds on leaves rather than the marketable portion of the crop, the bulb. Thrips feeding on onion causes silvery leaf spots that turn into white blotches along the leaves due to removal of cellular content followed by the development of silvery patches and curling of leaves (Bailey 1938). This injury reduces the photosynthetic ability of the plant (Molenaar 1984, Parrella and Lewis 1997) by destroying chlorophyll-rich leaf mesophyll (Molenaar 1984) and this may interfere with transportation of nutrients to the bulb (Parrella and Lewis 1997). Damage to onion caused by *T. tabaci* induces greater ethylene production (Kendall and Bjostad 1990) when the saliva from thrips salivary glands comes into contact with damaged tissues on the plant (Kendall and

Capinera 1990) and this induces ripening (bulb swelling) and senescence of leaves (Levy and Kedar 1970, Jackson and Osborne 1970). Thus, thrips infestations at the end of the growing season may help prepare the onion crop for harvest. However, permitting damage to occur late in the season could allow pathogens to infect the plant causing quality reductions in storage (Mayer et al. 1987).

Thrips tabaci still causes significant yield loss despite decades of research on control strategies worldwide (Lewis 1997b). *Thrips tabaci* feeding can reduce onion bulb weight (Kendall and Capinera 1987, Fournier et al. 1995, Rueda et al. 2007, Diaz-Montano et al. 2010) and cause up to 60% yield loss (Waiganjo et al. 2008). Young onion plants are more susceptible and prone to be killed by high *T. tabaci* infestations (Lewis 1973) and are relatively insensitive to thrips feeding late in the season; however, the damage increases with water stress (Parrella and Lewis 1997). Besides damage to the onion crop, *T. tabaci* adults and larvae can also feed on flower pedicels and buds and reduce seed yield in onions grown for seed production (Elmore 1949).

In addition to injury by feeding, *T. tabaci* transmits *Iris yellow spot virus* (IYSV) and is the only confirmed vector of this pathogen (Pozzer et al. 1999, Kritzman et al. 2001). IYSV was first identified on onion in southern Brazil in 1981 (Pozzer et al. 1994), and was confirmed in the USA in 1989 in Idaho and Oregon (Hall et al. 1993). IYSV has spread to other important onion producing states in the USA and worldwide (Gent et al. 2006). IYSV symptoms on leaves appear as lesions (i.e. straw-colored to white, dry, and sometimes elongate) along the edges (Gent et al. 2006). Studies conducted in Colorado (Gent et al. 2004) indicate that IYSV infection can reduce bulb size (Gent et al. 2004) and cause 100% crop loss (Pozzer et al. 1999). Many onion cultivars have been tested in field conditions and all of them became infected with the virus (du Toit and Pelter 2005, Diaz-Montano et al. 2010). In New

York, where the virus was found recently (Hoepting et al. 2007), symptoms of IYSV were mild to absent and appeared late in the season (Diaz-Montano et al. 2010, Hsu et al. 2010), which suggests that reductions in plant size and bulb weight were likely due to *T. tabaci* feeding rather than IYSV (Diaz-Montano et al. 2010). However, if IYSV infects onion plants early in the growing season, onion yield losses may increase (Diaz-Montano et al. 2010).

Feeding by *T. tabaci* can increase the incidence of the fungal pathogen, *Botrytis allii* Munn, in stored onions (Mayer et al. 1987). Onion plants with both *T. tabaci* and *Alternaria porri* (Ellis), the causal agent of purple blotch of onion, had larger lesions and suffered more damage. The fungus enters onion leaves through stomata and the epidermal cell layer but penetrates easier when the leaf surface has been damaged by thrips. Additionally, the infection moved from old leaves to young leaves where *T. tabaci* feeds (Thind and Jhooty 1982, McKenzie et al. 1993). Studies strongly suggest that *T. tabaci* predisposes onion plants to *A. porri*, therefore measures against *T. tabaci* should be considered while planning control of purple blotch of onion (Thind and Jhooty 1982).

Treatment Guidelines for *T. tabaci* on Onions

Treatment guidelines for *T. tabaci* on onion are impacted by a number of environmental and biological factors and vary regionally. Edelson et al. (1986) found that low populations of *T. tabaci*, ca. 9 thrips per plant for the whole season, did not impact onion yield significantly, but a population of 24 thrips per plant had a significant negative effect on yield. Other studies showed yield losses varying from 43% (Fournier et al. 1995) to 60% (Waiganjo et al. 2008). The greatest reduction in yield has been observed at the bulbing stage when populations are not controlled; only

10 thrips per plant can cause a 2 -3% and 7% bulb reduction in field and greenhouse conditions, respectively (Kendall and Capinera 1987).

It is difficult to determine accurate economic injury thresholds to onion because injury is caused indirectly by *T. tabaci* feeding on leaves rather than on the bulbs. However, some studies have been conducted. In Canada, Fournier et al. (1995) determined that seasonal (1988-1990) averages of 149 and 172 *T. tabaci* per plant resulted in yield losses of 35 and 43% in untreated plots, respectively, while an average of 35 thrips per plant did not cause significant losses. The economic thresholds calculated were 2.2 and 0.9 thrips per leaf for 1988 and 1989, respectively. In other studies, the following economic thresholds were recommended for *T. tabaci* on onion: 3 thrips per leaf in New York (Shelton et al. 1987); 1 thrips per leaf in Texas (Edelson et al. 1989); 0.9 thrips per leaf under early and severe drought conditions and 2.2 thrips per leaf during a season with a slight water deficit in Canada (Fournier et al. 1995) and 0.5 and 1.6 thrips per leaf during the dry season in Honduras (Rueda et al. 2007). There is not a unique economic threshold for thrips on onion (Fournier et al. 1995) or for any given pest without considering weather conditions (Pedigo et al. 1986, Fournier et al. 1995) or the efficacy of the insecticide used (Nault and Shelton 2010).

Management of *T. tabaci* in Onions

The most common method to control *T. tabaci* populations is the use of foliar insecticides, but *T. tabaci* is difficult to control because insects are found mainly in the narrow spaces between the inner leaves (Shelton et al. 1987) where spray coverage is difficult to accomplish. Additionally, some populations of *T. tabaci* have developed resistance to insecticides in several parts of the world (Martin et al. 2003, Shelton et al. 2003, 2006; MacIntyre Allen et al. 2005b, Herron et al. 2008, Morishita 2008).

Other studies have investigated the potential of other methods of control (biological control, host plant resistance, physical/mechanical control and cultural practices) to reduce or contain populations of *T. tabaci*. Management strategies of *T. tabaci* will be discussed in the following paragraphs.

Chemical Control

There is long history of use of insecticides to control *T. tabaci*. The first reports were the use of crude naphthalene (Maughan 1933, 1934) and crude naphthalene in combination with nicotine dust (Maughan 1934). A tartar emetic and brown sugar solution gave good control of *T. tabaci* on onion in the greenhouse, but failed to control thrips in the field (Anderson and Walker 1940); however, Ewart et al. (1944) cited different studies in the field that successfully controlled *T. tabaci* and increased onion yields using tartar emetic. Before the introduction of DDT, the main insecticide to control *T. tabaci* was foliar sprays of tartar emetic (Ashdown and Watkins 1948), but economical control of *T. tabaci* was not completely successful until DDT was introduced (Richardson and Wene 1956). There are several reports in which DDT provided good control of *T. tabaci* (Chapman et al. 1945, Smith and Goodhue 1945, Hely 1946, Ashdown and Watkins 1948, Mayeux and Wene 1950, Wilcox and Howland 1948, Jacks and Harrison 1953), but resistance to chlorinated hydrocarbons emerged in the middle 1950s. In Texas, 18 insecticides were evaluated to control *T. tabaci* and dieldrin, heptachlor, toxaphene, aldrin and endrin did not provide control when used alone (Richardson and Wene 1956). After this, organophosphates and carbamates were commonly used (Casida and Quistad 1998). In 1986, studies showed that ethyl parathion applications provided poor control of *T. tabaci* (Cranshaw 1989). Pyrethroids have been widely used for the control of *T. tabaci* in onion. Permethrin was registered for onion and widely applied, but by 1994

it failed to control *T. tabaci* (Davis et al. 1995). Another pyrethroid, λ -cyhalothrin, was registered in 1996 and many growers used it exclusively during 1997 and 1998. Some populations of *T. tabaci* in onion growing areas have developed resistance to pyrethroid and organophosphate insecticides in New York (Shelton et al. 2003, 2006), New Zealand (Martin et al. 2003), Canada (MacIntyre Allen et al. 2005b), Australia (Herron et al. 2008) and Japan (Morishita 2008).

Recently, several new selective insecticides belonging to novel classes of chemistry such as abamectin, cyantraniliprole, spinosad, spinetoram and spirotetramat have shown excellent control of *T. tabaci* infestations (Nault and Hessney 2008; Nault and Hessney 2010). In some cases, botanical insecticides have been effective against *T. tabaci*. Formulations of neem (*Azadirachta indica*) have prevented the development of first to second larval instar in the laboratory (Klein et al. 1993, Ascher et al. 2000). However, formulations of plant derived products including neem, *Chenopodium* sp. and eucalyptus have either failed or provided only mediocre control of *T. tabaci* in the onion field (Nault and Hessney 2010; Nault et al. 2010).

It is difficult to control *T. tabaci* with insecticides because eggs are protected under leaf tissues, prepupae and pupae are in the soil or in the inner space between the leaves, and some adults in the inner leaf spaces may escape control. Reinfestations from surrounding vegetation and immigration of thrips from nearby harvested onion fields may also contribute to rapid increases in populations.

When an insecticide fails to control insect pests in the field, it is necessary to conduct insecticide resistance assays. Field performance of insecticides may be affected by environmental factors and poor coverage of the crop (Shelton et al. 2003). An appropriate technique for conducting insecticide resistance assays would be to bring the insect populations from the field and culture them under laboratory conditions until adequate numbers are accessible for testing, but this presents several

problems with thrips. Thrips are difficult to keep in cages because of their small size and can contaminate or can be contaminated by other colonies and plant material on which thrips are reared may be contaminated. Also resistance may change over time, so rearing thrips for generations and then conducting a bioassay on these later generations should be a concern (Rueda and Shelton 2003). With these concerns in mind, Rueda and Shelton (2003) developed a technique to evaluate *T. tabaci* susceptibility of some insecticides and named it the thrips insecticide bioassay system (TIBS). Using TIBS, thrips are collected from onion plants in fields and placed directly into a plastic 0.5-ml microcentrifuge tube previously treated with an insecticide. Using this technique, studies have been able to identify *T. tabaci* resistance to different chemical insecticides within 24 h (Shelton et al. 2003, 2006, Rueda and Shelton 2003).

Insect species with a short life cycle and high fecundity can colonize crops rapidly and have a great potential to develop resistance to insecticides (Lewis 1997a). Polyphagous species are especially good at detoxifying a variety of plant toxins and this physiological adaptation can lead in the development of resistance to insecticides (Krieger et al. 1971). Insecticide resistance in thrips is a complex problem because it is necessary to understand genetic, biochemical and toxicological properties of the mechanisms of resistance of the insect (Lewis 1997a). Recently, Toda and Morishita (2009) studied mutations of the sodium channel in *T. tabaci* populations resistant to pyrethroid insecticides and identified three major mutations (M918T, T929I, and L1014F) responsible for this resistance.

Biological Control

There have been attempts to establish biological control agents for *T. tabaci* in different regions over 60 yr without significant success in the field (Parrella and Lewis

1997). In general, natural enemies affect only a small portion of the thrips population and their effect is unnoticed (Lewis 1973). *Thrips tabaci* usually seek protection in the inner leaves of onions and only when they come out of their refuge they are vulnerable to parasitoids and predators. Also, biological control in onion fields poses a monumental challenge because the crop is managed intensively with broad-spectrum insecticides and fungicides. However, the use of selective insecticides and action thresholds could create windows during the season in which biological control organisms could be helpful.

Waterhouse and Norris (1989) listed more than 90 natural enemies of *T. tabaci* worldwide, including predators and parasitoids insects (orders: Orthoptera, Hemiptera, Thysanoptera, Coleoptera, Neuroptera, Diptera and Hymenoptera), predacious mites (families: Anystidae, Erythraeidae and Phytoseiidae) and pathogenic fungi (classes: Zygomycetes and Hyphomycetes). The main predators of thrips include mites, heteropterans such as *Orius* sp., lacewing larvae, ladybird larvae, hoverfly larvae, small spiders and other thrips (Kirk 1997). The main parasitoids of thrips are endoparasitoid wasps (Loomans et al. 1995) of the family Eulophidae, including species from the genera *Ceranisus*, *Goetheana*, *Entedonastichus* and *Thripobius* (Kirk 1997). Adult wasps lay an egg inside the thrips larva. The wasp larva develops inside the thrips, killing it and emerging from the larva, prepupa or pupa (Kirk 1997).

Ceranisus menes parasitizes *T. tabaci* and other thrips species (Sakimura 1937 a, b cited by Kirk 1997). Some thrips species were able to escape parasitism by struggling, but larvae of *T. tabaci* do not. Samples taken from the field in Japan showed up to 88% parasitism of *T. tabaci* by *C. menes* and an average of 34%. The parasitoid wasps showed a density-dependent effect that seemed to regulate *T. tabaci* populations and the parasitism effectiveness increased through time (Sakimura 1937 a, b cited by Kirk 1997).

Butt and Brownbridge (1997) listed fungal pathogens that were isolated, or proven to be pathogenic to different thrips species. Fungi affecting *T. tabaci* includes *Neozygites parvispora*, *N. cucumeriformis*, *Zoophthora radicans* and *Entomophthora thripidum* (Class Zygomycetes); *Verticillium lecanii*, *Beauveria bassiana*, *Aspergillus* sp., *Paecilomyces fumosoroseus*, *Metarhizium anisopliae*, and; *Sporothrix* sp (Class Hyphomycetes). However, it is unlikely that fungi alone can reduce population of thrips effectively, or be a substitute for chemical insecticides (Butt and Brownbridge 1997).

There have been attempts to assess the potential of entomopathogenic nematodes for control of *T. tabaci*. Elad et al. (2004) conducted four field trials using spray applications of nematodes (*Steinernema feltiae* and *Heterorhabditis bacteriophora*) alone or in combination with pathogenic fungi (*Lecanicillium muscarium* former *Verticillium lecanii*, *Paecilomyces fumosoroseus* and *Beauveria bassiana*). In two trials, significant reductions in the number of thrips per plant were recorded for the treatments *Steinernema feltiae* + *Paecilomyces fumosoroseus*, and *Steinernema feltiae* + *Lecanicillium muscarium*, one week after the final application (three times in total). However, in the other two trials, there were no significant differences between the treatments and the control. In another study, Al-Siyabi et al. (2006) carried out experiments with the nematode, *Heterorhabditis indicus* against *T. tabaci* at different concentrations by using foliar and soil treatments. A treatment of 1.5 million nematodes per m² caused 70% mortality with soil applications and 55% with foliar applications. These studies demonstrate the success of entomopathogenic nematodes to control *T. tabaci*; however, more studies are needed to reveal the true impact for commercial production.

In summary, thrips control based on natural enemies does not appear to play a significant role in pest management programs in the field (Parrella and Lewis 1997).

Whether this can change with the use of more selective insecticides should be a topic of research.

Cultural Control

Traps are used in greenhouses to reduce and monitor insect pests (Jacobson 1997) and in the field to monitor them. In a field experiment, Kirk (1984) used water traps and observed that white color attracted twice as many *T. tabaci* as yellow and blue traps, but in a similar experiment the same colors (white, yellow and blue) were equally preferred (Czencz 1987). Pale blue was most attractive to *T. tabaci* compared with white, green, yellow, grey and red traps (Lu 1990). In greenhouse conditions, *T. tabaci* were more attracted to shades of blue and yellow than white (Brødsgaard 1993). MacIntyre-Allen et al. (2005a) compared sticky traps with *T. tabaci* counts in onion fields and found that white sticky traps detected thrips earlier than plant counts. Recently, Davidson et al. (2009) studied the effect of pyridine compounds on *T. tabaci* populations attracted to white water traps in an onion field and observed that ethyl isonicotinate, and methyl and ethyl nicotinate caught 18, 12, and 4 times more thrips, respectively, than the control. In a similar experiment, Wogin et al. (2010) combined ethyl isonicotinate and ethyl nicotinate and caught 5–9 times more *T. tabaci* than traps with ethyl nicotinate only, but caught similar numbers to traps with ethyl isonicotinate only.

Mechanical barriers and UV-reflectance have been examined for reducing thrips infestations (Parrella and Lewis 1997). Larentzaki et al. (2008a) studied the effect of kaolin particle film on *T. tabaci* in onion and found that it had significant negative effects on oviposition, feeding and development of *T. tabaci* under laboratory conditions and thrips populations were significantly lower on kaolin-treated plots in field conditions. Lu (1990) observed that silver mulches more effectively repelled *T. tabaci* when shallots were planted at 12x12 cm spacing than when planted at 3x3 cm

and when utilized at the seedling stage than at plant maturity. Larentzaki et al. (2008b) evaluated the impact of straw mulch on *T. tabaci* in onion. In the field, they observed that straw mulch-treated plots had significantly less thrips and action thresholds were reached in straw mulch treatments 1-2 weeks later than in control plots but yield was not significantly different between plots. In laboratory conditions, pupation was reduced by 54% in onion plants grown in straw mulch compared to a bare soil treatment.

Sanitation through destruction of cull onions, volunteer onion plants and weed hosts in the field after harvest is essential because they can serve as a *T. tabaci* overwintering site (Larentzaki et al. 2007). Volunteer onion plants, produced from cull onions, are sometimes found in high densities in onion fields when the onion crop is not present and they serve as a suitable host for thrips before the onions are planted in the spring and after onions are harvested in the fall. Because volunteer onions do not remain green during the winter, onion culls may serve as overwintering site, as well as feeding and oviposition sites in the spring (Larentzaki et al. 2007). Removal of volunteer onion plants is also important because they are one of the few sources of primary inoculum of IYSV (Gent et al. 2006). *Thrips tabaci* also has been found colonizing different weeds species late in the fall (Larentzaki et al. 2007, Smith 2010).

Heavy rains can dislodge thrips and leave droplets on the leaves and drown *T. tabaci*, causing dramatic populations decreases (Harris et al. 1935, North and Shelton 1986a). Overhead irrigation of onion crops can cause similar reductions and this effect was comparable with the use of insecticides in areas in Australia (Passlow 1957). However, this may be difficult to implement in large-scale onion fields and our experience reducing *T. tabaci* populations with overhead irrigation has given inconsistent results.

In field conditions, intercropping of vegetables with other plant species has been shown to reduce pest populations and may reduce or eliminate chemical control (Theunissen 1994). Intercropping has been successful in reducing *T. tabaci* infestations in tropical and temperate climates (Parrella and Lewis 1997). In Egypt, Afifi and Haydar (1990) reported that intercropping of onion and garlic with tomato reduced infestations of *T. tabaci* by 80%. In England, intercropping of onions with carrots decreased *T. tabaci* populations by 50% and it was more effective when single rows of each crop were closely alternated, possibly because carrot foliage hid the onions from thrips view (Uvah and Coaker, 1984).

Host Plant Resistance

Host plant resistance is an important foundation of integrated pest management (IPM) (Panda and Khush 1995, Kennedy 2008) and may offer a long-term solution to *T. tabaci* control and reduce the use of insecticides, which would lower environmental hazards and minimize the evolution of resistance to insecticides.

It had been reported that onion cultivars with white bulbs were more resistant to *T. tabaci* than cultivars with red bulbs (Verma 1966, Lall and Singh 1968); however, further work by Brar et al. (1993) did not find any such relationship. In New York State, MacLeod (1933) categorized 20 onion cultivars as susceptible or resistant by counting the number of *T. tabaci* present on the plants every 2 wk during the period of infestation and suggested eight of the cultivars were resistant. However, caution should be observed with results from such ‘choice tests’ in the field because resistance may not hold up when only one cultivar is grown.

Jones et al. (1934) observed that inner leaves of susceptible onion cultivars were flat and closer together, which provided more shelter for *T. tabaci*. On the contrary, the most resistant cultivar, ‘White Persian’, has inner leaves with a circular

shape that were more separated from each other. When leaves were tied together artificially, *T. tabaci* populations increased on ‘White Persian’ suggesting the architecture of the plants was important. Jones et al. (1935) compared *T. tabaci* populations on 44 onion cultivars with the resistant cultivar ‘White Persian’. All cultivars tested had significantly higher numbers of *T. tabaci* than the resistant cultivar, which has thick, light green leaves and an open type of canopy. A similar type of leaf structure was observed in the cultivar ‘Nebuka’, which had less *T. tabaci* compared to three other onion cultivars (Coudriet et al. 1979).

Pawar et al. (1987) screened 64 onion cultivars for resistance to *T. tabaci* and found that 17 that had the lowest number of *T. tabaci* larvae had leaves with a circular shape and wider angle between the central leaves. In a similar study, three of 28 onion cultivars classified as resistant had a wider angle between central leaves (Patil et al. 1988). Hudák and Péntzes (2004) associated low populations of *T. tabaci* with the shape of leaves and the angle of divergence of the two innermost leaves. In another study six of 61 genotypes screened for resistance sustained fewer *T. tabaci* than the other cultivars (Brar et al. 1993). Loges et al. (2004a, 2004b) showed a relationship with the low number of larvae found on the cultivar ‘Duquesa’ with the fewest leaves and largest angle between the central leaves, compared to seven other onion cultivars.

In a recent study, Diaz-Montano et al. (2010) screened 49 onion cultivars and found 11 resistant to *T. tabaci*. All the resistant cultivars had yellow-green colored foliage compared to the susceptible ones that all had blue-green color foliage. Although the authors did not examine the morphological or chemical basis for these color differences, they suggested that such differences in color are strongly associated with resistance.

Conclusions

Thrips tabaci is a well-established primary pest of onion worldwide that causes yield reductions by its direct feeding and, more recently, by its transmission of IYSV and other pathogens. Management of *T. tabaci* over the last 60 years has relied primarily on the use of insecticides, but this in turn has led to many cases of insecticide resistance. While insecticides will likely continue to be useful as components of an overall IPM program, there is an urgent need to incorporate other strategies like those mentioned in this review.

One seemingly underutilized strategy is the use of host plant resistance. Although published studies since the 1930s have suggested this as a viable strategy, it does not appear that commercial companies have emphasized this strategy in their research and development programs. Most likely, this is because the factor(s) responsible for resistance have not been well defined and thus cannot be easily incorporated into a breeding program. Cultivars that we have recently identified as being resistant do include some commercial cultivars and we have suggested such resistance is associated with leaf color (Diaz-Montano et al. 2010), but considerably more work needs to be done before such knowledge can be incorporated into a breeding program that would produce cultivars that are commercially acceptable for farmers and consumers.

The situation with developing resistance to IYSV is more complex since none of the cultivars we examined showed any tolerance to this emerging disease and we are not aware of any other germplasm showing resistance. If onion cultivars, or if cultural practices can be implemented, that reduce the likelihood that *T. tabaci* will land on and colonize onions, it would be expected that the incidence of IYSV would be reduced. However, a more likely successful strategy would be to incorporate genes

for resistance to IYSV into commercially acceptable onions, but we are not aware of any resistant germplasm. In such cases, it may be that genetically engineering onions to be resistant to IYSV may be the only viable solution. This strategy has proven extremely effective in controlling Papaya ringspot virus in papaya and several viruses in summer squash (Shelton et al. 2008).

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REFERENCES

- Affi, F. M. L., and M. F. Haydar. 1990.** Effect of different intercropping systems on onion and garlin infestation with the “cotton and onion thrips”, *Thrips tabaci* Lind. Bull. Fac. Agric., Univ. of Cairo. 41: 639-648.
- Al-Siyabi, A.A, M. M. Kinawy, M. Al-Ansri, A. N. Mahar, S.R. Gowen, and N. G. Hague. 2006.** The susceptibility of onion thrips, *Thrips tabaci* to *Heterorhabditis indicus*. Commun. Agric. Appl. Biol. Sci. 71 :239-243.
- Ananthakrishnan, T.N. 1973.** Thrips: biology and control. Macmillan, India. 120 p.
- Ananthakrishnan, T.N. 1990.** Reproductive biology of thrips. Indira Publishing House, Oak Park, MI. 158 p.
- Anderson, L. D., and H. G. Walker. 1940.** Notes on the control of onion thrips. J. Econ. Entomol. 33: 278-280.
- Arrieche, N., R. Paz, A. Montagne, and J. Morales. 2006.** Estudios biológicos de *Thrips tabaci* Lindeman (Thysanoptera: Thripidae) en cebolla, en el estado Lara, Venezuela. Bioagro. 18: 149-156.
- Ashdown, D., and T. C. Watkins. 1948.** Field studies on control of onion thrips in New York. J. Econ. Entomol. 41: 378-382.
- Ascher, K.R.S. , J. Meisner, and M. Klein. 2000.** Neem-based biopesticides against the Western flower thrips (WFT) and the onion thrips, pp. 87. In Abstracts of presentations on selected topics at The XIVth International plant protection congress (IPPC) 2. NEEM (*Azadirachta indica*), 25-30 July 1999, Jerusalem, Israel. Phytoparasitica. 28: 87-90.
- Bailey, S. F. 1934.** A winter study of the onion thrips in California. California State Dept. Agr. Mo. Bull. 23: 149-152.

- Bailey, S. F. 1938.** Thrips of economic importance in California. Univ. California, Coll. Agric., Agric. Exp. Stn. Cir. 346.
- Bournier, A. 1983.** Les thrips: biologie, importance agronomique. INRA, Paris. 128 p.
- Brar, K. S., A. S. Sidhu, and M. L. Chadha. 1993.** Screening onion varieties for resistance to *Thrips tabaci* Lind. and *Helicoverpa armigera* (Hubner). J. Insect Sci. 6: 123-124.
- Brødsgaard, H. F. 1993.** Coloured sticky traps for thrips (Thysanoptera: Thripidae) monitoring on glasshouse cucumbers. Bulletin OILB/SROP. 16: 19-22.
- Butt, T. M., and M. Brownbridge. 1997.** Fungal pathogens of thrips, pp. 399-433. In T. Lewis (ed.), Thrips as crop pests. CAB International, New York, NY.
- Capinera, J. L. 2001.** Handbook of vegetable pests. Academic Press, New York, NY. 729 p.
- Casida, J. E., and G. B. Quistad. 1998.** Golden age of insecticide research: Past, Present, or Future? Annu. Rev. Entomol. 43: 1-16.
- Chambers. W. S., and R. W. Sites. 1989.** Overwintering thrips fauna in coplands of the Texas south plains. Southwest. Entomol.. 14: 325-328.
- Chapman, A. J., L. C. Fife, and R. L. McGarr. 1945.** DDT for the control of onion thrips. J. Econ. Entomol. 38: 608-609.
- Chittenden, F. H. 1913.** Insects injurious to the onion crop. Yearbook of the U.S. Dept. Agric. 1912. p. 319-334.
- Coudriet, D. L., A. N. Kishaba, J. D. McCreight, and G. W. Bohn. 1979.** Varietal resistance in onions to thrips. J. Econ. Entomol. 72: 614-615.
- Cranshaw, W. S. 1989.** Control of organophosphate resistant onion thrips, 1986. Insectic. Acaricide Tests. 14: 128.

- Czencz, K. 1987.** The role of coloured traps in collecting thrips fauna, pp. 426-435. *In* J Holman, J. Pelikán, A. F. G. Dixon and L. Weismann (eds.), Population structure, genetics and taxonomy of aphids and Thysanoptera. Proceedings of international symposia, held at Smolenice, Czechoslovakia, September 9-14, 1985. SPB Academic Publishing, the Netherlands.
- Davis, M., Y. Anandwala, M. Bommarito, and E. Grafus. 1995.** Onion thrips control, 1994. *Arthropod Manage. Tests.* 20: 99.
- Davidson, M. M., R. C. Butler, and D. A. J. Teulon. 2009.** Pyridine compounds increase thrips (Thysanoptera: Thripidae) trap capture in an onion crop. *J. Econ. Entomol.* 102: 1468-1471.
- Diaz-Montano, J., M. Fuchs, B. A. Nault and A. M. Shelton. 2010.** Evaluation of onion cultivars for resistance to onion thrips (Thysanoptera: Thripidae) and Iris Yellow Spot Virus. *J. Econ. Entomol.* 103: 925-937.
- du Toit, L. J., and G. Q. Pelter. 2005.** Susceptibility of storage onion cultivars to iris yellow spot in the Columbia Basin of Washington, 2005. *Biol. Cultural Tests.* 20: V006.
- Edelson, J.V., B. Cartwright, and T. A. Royer. 1986.** Distribution and impact of *Thrips tabaci* (Thysanoptera: Thripidae) on onion. *J. Econ. Entomol.* 79: 502-505.
- Edelson, J. V., and J. J. Magaro. 1988.** Development of onion thrips, *Thrips tabaci* Lindeman, as a function of temperature. *Southwest. Entomol.* 13: 171-176.
- Edelson, J.V., B. Cartwright, and T. A. Royer. 1989.** Economics of controlling onion thrips (Thysanoptera: Thripidae) on onions with insecticides in south Texas. *J. Econ. Entomol.* 82: 561-564.

- Elad, Y., I. Pertot, and A. Enkegaard. 2004.** Combined use of insect pathogenic fungi and nematodes against the onion thrips, *Thrips tabaci*, in the field. Bulletin OILB/SROP. 27: 141-143.
- Elmore, J. C. 1949.** Thrips injury to onions grown for seed. J. Econ. Entomol. 42:756-760.
- Ewart, W. H., T. C. Watkins, and D. Ashdown. 1944.** Insecticidal uses of tartar emetic: against onion thrips in New York. J. Econ. Entomol. 37: 269-276.
- [FAO] Food and Agriculture Organization of the United Nations. 2009.** FAO statistical yearbook 2009. FAO Statistics Division. (<http://faostat.fao.org/>). Date accessed: 14-VII-2010.
- Fournier, F., G. Boivin, and R.K. Stewart. 1995.** Effect of *Thrips tabaci* (Thysanoptera: Thripidae) on yellow onion yields and economic thresholds for its management, J. Econ. Entomol. 88: 1401-1407.
- Gangloff, J. L. 1999.** Population dynamics and insecticide resistance of onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae) in onions. Ph.D. Dissertation, Cornell University, Ithaca, NY.
- Gawaad, A. A. A., and A. Y. El-Shazli. 1970.** Studies on *Thrips tabaci* Lindman. VI. New stage in life cycle. Z. Angew. Entomol. 66: 395-398.
- Gawaad, A. A. A., and A. Y. El-Shazli. 1971.** Studies on *Thrips tabaci* Lindman. VII. Effect of food on the life cycle. Z. Angew. Entomol. 67: 27-30.
- Gent, D. H., H. R. Schwartz, and R. Khosla. 2004.** Distribution and incidence of *Iris yellow spot virus* in Colorado and its relation to onion plant population and yield. Plant Dis. 88: 446-452.
- Gent, D. H., L. J. du Toit, S. F. Fichtner, S. K. Mohan, H. R. Pappu, and H. F. Schwartz. 2006.** *Iris yellow spot virus*: an emerging threat to onion bulb and seed production. Plant Dis. 90: 1468-1480.

- Ghabn, A. A. A. E. 1948.** Contribution to the knowledge of the biology of *Thrips tabaci* Lind. in Egypt. Bull. Soc. Fouad. I Ent. 32: 123-174.
- Gillette, C.P. 1893.** A few common insect pests. Colorado State Agric. College, Agric. Exp. Stn. Bull. 24. 16 p.
- Guzman, S. P., P. Salazar, A. Trochez, J. De la Cruz. 1996.** Ciclo de vida, hábitos y comportamiento de *Thrips tabaci* Lindeman en cebolla de bulbo (*Allium cepa*) Rev. Colomb. Entomol. 22: 93-98.
- Hall, J. M., Mohan, K., Knott, E. A. and Moyer, J. W. 1993.** Tospoviruses associated with scape blight of onion (*Allium cepa*) seed crops in Idaho. Plant Dis. 77: 952.
- Harding, J. A. 1961.** Effect of migration, temperature, and precipitation on thrips infestations in south Texas. J. Econ. Entomol. 54: 77-79.
- Harris, H. M., C. J. Drake, and H. D. Tate. 1935.** Observation on the onion thrips (*Thrips tabaci* Lind.) Iowa St. Coll. J. Sci. 10: 155-171.
- Hely, P. C. 1946.** Control of *Thrips tabaci* on onions. Experiments with DDT and tartar emetic. Agric. Gaz. N. S. W. 57: 467-471.
- Herron, G. A., T. M. James, and J. H. Mo. 2008.** Australian populations of onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), are resistant to some insecticides used for their control. Aust. J. Entomol. 47: 361-364.
- Hoepting, C. A., H. F. Schwartz, and H. R. Pappu. 2007.** First report of *Iris yellow spot virus* on onion in New York. Plant Dis. 91: 327.
- Horsfall, J. L. 1921.** Sources of infestation of *Thrips tabaci* in Iowa. J. Econ. Entomol. 14: 493-496.

- Hsu, C. L., C. A. Hoepting, M. Fuchs, A. M. Shelton, and B. A. Nault. 2010.** Temporal dynamics of Iris Yellow Spot Virus and its vector, *Thrips tabaci* (Thysanoptera: Thripidae), in seeded and transplanted onion fields. Environ. Entomol. 39: 266-277.
- Hudák, K., and B. Péntzes. 2004.** Factors influencing the population of the onion thrips on onion. Acta Phytopathol. Entomol. Hung. 39: 193-197.
- Jacks, H., and R. A. Harrison. 1953.** Control of onion thrips. II. Final selection of insecticides. N. Z. J. Sci. Tech. A. 35: 164-167.
- Jackson, M. B., and D. J. Osborne. 1970.** Ethylene, the natural regulator of leaf abscission. Nature. 225: 1019-1022.
- Jacobson, R. J. 1997.** Integrated pest management (IPM) in glasshouses, pp. 639-666. In T. Lewis (ed.), Thrips as crop pests. CAB International, New York, NY.
- Jones, H. A., S. F. Bailey, and S. L. Emsweller. 1934.** Thrips resistance in the onion. Hilgardia. 8: 215-232.
- Jones, H. A., S. F. Bailey, and S. L. Emsweller. 1935.** Field studies of *Thrips tabaci* Lind. with special reference to resistance in onions. J. Econ. Entomol. 28: 678-680.
- Kendall, D. M., and J. L. Capinera. 1987.** Susceptibility of onion growth stages to onion thrips (Thysanoptera: Thripidae) damage and mechanical defoliation. Environ. Entomol. 16: 859-863.
- Kendall, D. M., and J. L. Capinera. 1990.** Geographic and temporal variation in the sex ratio of onion thrips. Southwest. Entomol. 15: 80-88.
- Kendall, D. M., and L. B. Bjostad. 1990.** Phytohormone Ecology: herbivory by *Thrips tabaci* induces greater ethylene production in intact onions than mechanical damage alone. J. Chem. Ecol. 16: 981-991.

- Kennedy, G. G. 2008.** Integration of insect-resistant genetically modified crops within IPM programs, pp. 1-26. In J. Romeis, A. M. Shelton and G.G. Kennedy (eds.), Integration of insect-resistant genetically modified crops within IPM programs. Springer, the Netherlands.
- Kirk, W. D. J. 1984.** Ecologically selective coloured traps. *Ecol. Entomol.* 9: 35-41.
- Kirk, W. D. J. 1997.** Distribution, abundance and population dynamics, pp. 217-257. In T. Lewis (ed.), *Thrips as crop pests*. CAB International, New York, NY.
- Klein, M., J. Meisner, E. Ben-Moshe, N. E. Nemny, I. Caspy, and K. R. S. Ascher. 1993.** Formulations of neem (*Azadirachta indica*) seed extracts inhibit growth of nymphs of the onion thrips, *Thrips tabaci*. *Hassadeh*. 74: 189-193.
- Krieger, R. L., P. P. Feeny, and C. F. Wilkinson. 1971.** Detoxication enzymes in the guts of caterpillars: an evolutionary answer to plant defenses? *Science*. 579-581.
- Kritzman, A., M. Lampel, B. Raccach, and A. Gera. 2001.** Distribution and transmission of *Iris yellow spot virus*. *Plant Dis.* 85: 838-842.
- Lall, B. S., and L. M. Singh. 1968.** Biology and control of the onion thrips in India. *J. Econ. Entomol.* 61: 676-679.
- Larentzaki, E., A. M. Shelton, F. R. Musser, B. A. Nault, and J. Plate. 2007.** Overwintering locations and hosts for onion thrips (Thysanoptera: Thripidae) in the onion cropping ecosystem in New York. *J. Econ. Entomol.* 100: 1194-1200.
- Larentzaki, E., A. M. Shelton, and J. Plate. 2008a.** Effect of kaolin particle film on *Thrips tabaci* (Thysanoptera: Thripidae), oviposition, feeding and development on onions: a lab and field case study. *Crop Prot.* 27: 727-734.

- Larentzaki, E., J. Plate, B. A. Nault, and A. M. Shelton. 2008b.** Impact of straw mulch on populations of onion thrips (Thysanoptera: Thripidae) in Onion. J. Econ. Entomol. 101: 1317-1324.
- Levy, D., and N. Kedar. 1970.** Effect of Ethrel on growth and bulb initiation in onion. Hortscience. 5: 80-82.
- Lewis, T. 1973.** Thrips: their biology, ecology and economic importance. Academic Press, London. 349 p.
- Lewis, T. 1997a.** Chemical control, pp. 567-593. In T. Lewis (ed.), Thrips as crop pests. CAB International, New York, NY.
- Lewis, T. 1997b.** Pest thrips in perspective, pp. 1-13. In T. Lewis (ed.), Thrips as crop pests. CAB International, New York, NY.
- Lindeman, K. 1889.** Die schädlichsten insekten des tabak in Bessarabien. Bull. Soc. Imp. Nat. Moscou. 2: 10-77.
- Loges, V., M.A. Lemos, L. V. Resende, D. Menezes, J.A. Candeia, and V. F. Santos. 2004a.** Correlações entre caracteres agronômicos associados à resistência a tripes em cebola. Hortic. Bras. 22: 624-627.
- Loges, V., M.A. Lemos, L. V. Resende, D. Menezes, J.A. Candeia, and V. F. Santos. 2004b.** Resistência de cultivares e híbridos de cebola a tripes. Hortic. Bras. 22: 222-225.
- Loomans, A. J. M., J. C. van Lenteren, M. G. Tommasini, S. Maini, and J. Riudavets. 1995.** Biological control of thrips pests: A review on thrips parasitoids. Wageningen Agricultural University Papers. 95: 89-201.
- Lu, F. M. 1990.** Color preference and using silver mulches to control the onion thrips, *Thrips tabaci* Lindeman. Chin. J. Entomol. 10: 337-342.

MacIntyre-Allen, J. K., C. D. Scott-Dupree, J. H. Tolman, and C. R. Harris.

2005a. Evaluation of sampling methodology for determining the population dynamics of onion thrips (Thysanoptera: Thripidae) in Ontario onion fields. J. Econ. Entomol. 98: 2272-2281.

MacIntyre Allen, J. K., C. D. Scott-Dupree, J. H. Tolman, and C. R. Harris.

2005b. Resistance of *Thrips tabaci* to pyrethroid and organophosphorus insecticides in Ontario, Canada. Pest Manag. Sci. 61: 809-815.

MacLeod, G. F. 1933. Some examples of varietal resistance of plants to insect attacks. J. Econ. Entomol. 26: 62-67.

Martin, N. A., P. J. Workman and R. C. Butler. 2003. Insecticide resistance in onion thrips (*Thrips tabaci*) (Thysanoptera: Thripidae). New Zeal. J. Crop Hort. 31: 99-106.

Maughan, F. B. 1933. Naphthalene for the control of the onion thrips. J. Econ. Entomol. 26: 143-147.

Maughan, F. B. 1934. Further studies on the control of the onion thrips. J. Econ. Entomol. 27: 109-112.

Mayer, D. F., J. D. Lunden, and L. Rathbone. 1987. Evaluation of insecticides for *Thrips tabaci* (Thysanoptera: Thripidae) and effects of thrips on bulb onions. J. Econ. Entomol. 80: 930-932.

Mayeux, H. S., and G. P. Wene. 1950. Control of onion thrips with low volume sprays. J. Econ. Entomol. 43: 908-912.

McKenzie, C. L., B. Cartwright, M. E. Miller, and J. V. Edelson. 1993. Injury to onions by *Thrips tabaci* (Thysanoptera: Thripidae) and its role in the development of purple blotch. Env.Ent. 22: 1266-1277.

- Mo, J., S. Munro, A. Boulton, and M. Stevens. 2008.** Within-plant distribution of onion thrips (Thysanoptera: Thripidae) in onions. *J. Econ. Entomol.* 101:1331-1336.
- Molenaar, N. D. 1984.** Genetics, thrips (*Thrips tabaci* L.) resistance and epicuticular wax characteristics of nonglossy and glossy onions (*Allium cepa* L.) Ph.D. Dissertation, University of Wisconsin, Madison, WI.
- Morishita, M. 2008.** Pyrethroid-resistant onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), infesting persimmon fruit. *Appl. Entomol. Zool.* 43: 25-31.
- Morison, G. D. 1957.** A review of British glasshouse Thysanoptera. *Trans. Roy. Ent. Soc. London.* 109: 467-520.
- Moritz, G. 1997.** Structure, growth and development, pp. 15-63. In T. Lewis (ed.), *Thrips as crop pests*. CAB International, New York, NY.
- Moritz, G., D. C. Morris, and L. A. Mound. 2001.** ThripsID - Pest thrips of the world. An interactive identification and information system. Cd-rom published for ACIAR by CSIRO Publishing, Melbourne.
- Mound, L. A. 1967.** The British species of the genus *Thrips* (Thysanoptera). *Entomol. Gaz.* 18: 13-22.
- Mound, L. A. 1973.** Thrips and whitefly, pp. 229-242 . In A. J. Gibbs (ed.), *Viruses and invertebrates*, Elsevier, New York, NY.
- Mound, L. A. 1997.** Biological diversity, pp. 197-215. In T. Lewis (ed.), *Thrips as crop pests*. CAB International, New York, NY.
- Mound, L.A., and A.K. Walker. 1982.** Terebrantia (Insecta: Thysanoptera). *Fauna of New Zeland.* No. 1. 113p.

- Murai, T., and Toda, S. 2001.** Variation of *Thrips tabaci* in colour and size, pp. 377-378. In R. Marullo & L. Mound (eds.), *Thrips, Plants, Tospoviruses: the Millennial Review*. Proceedings of the 7th International Symposium on Thysanoptera, 2-7 July 2001, Reggio Calabria, Italy. CSIRO, Australia.
- Nakahara, S. 1991.** Systematics of Thysanoptera, pear thrips and other economic species, pp.41-59. In: B.L. Parker, M. Skinner, T. Lewis (eds.), *Towards understanding Thysanoptera*. U.S.D.A., General Tech. Rep. NE-147. Radnor, PA USDA, Forest Service, Northeastern Forest Exp. Sta.
- Nakahara, S. 1994.** The genus *Thrips* Linnaeus (Thysanoptera: Thripidae) of the new world. U.S.D.A., Tech. Bull. 1822, 183p.
- Nault, B. A., and A. M. Shelton. 2010.** Impact of insecticide efficacy on developing action thresholds for pest management: a case study of onion thrips (Thysanoptera: Thripidae) on onion. *J. Econ. Entomol.* 103: 1315-1326.
- Nault, B. A., and M. L. Hessney. 2008.** Onion thrips control in onion, 2007. *Arthropod Manage. Tests.* 33: E20.
- Nault, B. A., and M. L. Hessney. 2010.** Onion thrips control in onion, 2009. *Arthropod Manage. Tests.* (in press).
- Nault, B. A., A. M. Shelton, J. L. Gangloff-Kaufmann, M. E. Clark, J. L. Werren, J.C. Cabrera-La Rosa, and G. G. Kennedy. 2006.** Reproductive modes in onion thrips (Thysanoptera: Thripidae) populations from New York onion fields. *Environ. Entomol.* 35: 1264-1271.
- Nault, B. A., C. L. Hsu, E. A. Smith, M. L. Hessney, M. Fuchs and A. M. Shelton. 2010.** Managing onion thrips and status of *Iris yellow spot virus* in New York, pp. 113-117. In: *Proceedings of the 2010 Empire State Fruit and Vegetable Expo*. January 25-27, 2010. Syracuse, NY. Cornell Cooperative Extension and New York State Vegetable Growers Association.

- North, R. C., and A. M. Shelton. 1986a.** Ecology of Thysanoptera within cabbage fields. *Environ. Entomol.* 15: 520–526.
- North, R. C., and A. M. Shelton. 1986b.** Overwintering of the onion thrips, *Thrips tabaci* (Thysanoptera: Thripidae), in New York. *Environ. Entomol.* 15: 695–699.
- Osborn, H. and, C.W. Mally. 1895.** The western onion thrips (*Thrips alii* Gilette). Iowa Agric. College Exp. Stn. Bull. 27: 139-142.
- Packard, A.S. 1872.** Insects injurious to field crops: the onion thrips, pp. 5-8. In: Second annual report on the injurious and beneficial insects of Massachusetts. Wright and Potter, Boston.
- Panda, N., and G. S. Khush. 1995.** Host plant resistance to insects. CAB International, UK.
- Parrella, M. P., and T. Lewis. 1997.** Integrated pest management (IPM) in field crops, pp. 595-614. In T. Lewis (ed.), *Thrips as crop pests*. CAB International, New York, NY.
- Passlow, T. 1957.** Control of *Thrips tabaci* Lind. in onion crops in the Lockyer Valley. *Queensl. J. Agr. Anim. Sci.* 14: 53-72.
- Patil, A. P., R. N. Nawale, D. S. Ajri, and P. R. Moholkar. 1988.** Field screening of onion cultivars for their reaction to thrips. *Indian Cocoa, Arecanut & Spices J.* 12: 10-11.
- Pawar, D. B., U. N. Mote, P. N. Kale, and D. S. Ajri. 1987.** Identification of resistant sources for thrips in onion. *Curr. Res. Report.* 3: 115-117.
- Pedigo, L. P., S. H. Hutchins, and L. G. Higley. 1986.** Economic injury levels in theory and practice. *Annu. Rev. Entomol.* 31: 341-368.
- Pergande, T. 1895.** Observations on certain Thripidae. *Insect Life.* 7: 390–395.

- Pozzer, L., T. Nagata, M. I. Lima, E. W. Kitajima, R. de O. Resende, and A. C. de Ávila. 1994.** “Sapeca”: An onion disease in the Sub-Médio São Francisco region, Brazil, is caused by a tospovirus with a serologically distinct nucleocapsid protein. *Fitopatol. Bras.* 19: 321.
- Pozzer, L., I. C. Bezerra, R. Kormelink, M. Prins, D. Peters, R. de O. Resende, and A. C. de Ávila. 1999.** Characterization of a tospovirus isolate of iris yellow spot virus associated with a disease in onion fields in Brazil. *Plant Dis.* 83: 345-350.
- Richardson, B. H., and G. P. Wene. 1956.** Control of onion thrips and its tolerance to certain chlorinated hydrocarbons. *J. Econ. Entomol.* 49: 333-335.
- Rueda, A., and A. M. Shelton. 2003.** Development of a bioassay system for monitoring susceptibility in *Thrips tabaci*. *Pest Manag. Sci.* 59: 553-558.
- Rueda, A., F. R. Badenes-Perez, and A. M. Shelton. 2007.** Developing economic thresholds for onion thrips in Honduras. 26: 1099-1107. *Crop Prot.*
- Sakimura, K. 1937.** The life and seasonal histories of *Thrips tabaci* Lind. in the vicinity of Tokyo, Japan. *Oyo Dobuts. Zasshi.* 9: 1-24.
- Salas, J., G. Morales, O. Mendoza, C. Alvarez, and A. Parra. 1993.** Biología y hábitos de *Thrips tabaci* Lindeman (Thysanoptera: Thripidae) en cebolla, *Allium cepa* L. *Agron. Trop.* 43: 173-183.
- Shelton, A. M., J. P. Nyrop, R. C. North, C. Petzoldt, and R. Foster. 1987.** Development and use of a dynamic sequential sampling program for onion thrips, *Thrips tabaci*, on onions. *J. Econ. Entomol.* 80: 1051-1056.
- Shelton, A. M., B. A. Nault, J. Plate, and J. Z. Zhao. 2003.** Regional and temporal variation in susceptibility to λ -Cyhalothrin in onion thrips, *Thrips tabaci* (Thysanoptera: Thripidae) in onion fields in New York. *J. Econ. Entomol.* 96: 1843-1848.

- Shelton, A. M., J. Z. Zhao, B. A. Nault, J. Plate, F. R. Musser, and E. Larentzaki. 2006.** Patterns of insecticide resistance in onion thrips (Thysanoptera: Thripidae) in onion fields in New York. *J. Econ. Entomol.* 99: 1798-1804.
- Shelton, A. M., M. Fuchs, and F. Shotkowski. 2008.** Transgenic vegetables and fruits for control of insect and insect-vectored pathogens, pp. 249-272. In J. Romeis, A. M. Shelton and G.G. Kennedy (eds.), *Integration of insect-resistant genetically modified crops within IPM programs*. Springer, the Netherlands.
- Shipley, A. E. 1887.** Onion disease at Bermuda (*Peronospora schleideniana* De Bary) *Bull. Misc. Inf., Kew. No.* 10: 1-23.
- Shirck, F. H. 1951.** Hibernation of onion thrips in southern Idaho. *J. Econ. Entomol.* 44: 1020-1021.
- Sites, R. W., and W. S. Chambers. 1990.** Initiation of vernal activity of *Frankliniella occidentalis* and *Thrips tabaci* on the Texas south plains. *Southwest. Entomol.* 15: 339-343.
- Sites, R. W., W. S. Chambers, and B. J. Nichols. 1992.** Diel periodicity of thrips (Thysanoptera: Thripidae) dispersion and the occurrence of *Frankliniella williamsi* on onions. *J. Econ. Entomol.* 85: 100-105.
- Slingerland, M.V. 1896.** The “white blast” in onions. *Rural New Yorker.* 55: 561.
- Smith, E. 2010.** Identifying weed species hosts for onion thrips (*Thrips tabaci* Lindeman) and their potential as sources of *Iris yellow spot virus* (Bunyaviridae: Tospovirus) in New York onion fields. M. S. Thesis, Cornell University, Ithaca, NY. 89 p.
- Smith, F. F., and L. D. Goodhue. 1945.** DDT aerosols to control onion thrips and other pests in greenhouses. *J. Econ. Entomol.* 38: 173-9.
- Srinivasan, S., S. Lingappa, and Gurumurthy. 1981.** Dispersion of onion thrips, *Thrips tabaci* Lindeman. *Entomol.* 6: 275-277.

- Stannard, L. J. 1968.** The thrips, or Thysanoptera, of Illinois. Illinois Nat. Hist. Surv. Bull. 29: 215-552.
- Thaxter, R. 1890.** Notes in answer to inquiries concerning injurious insects. Connecticut Agric. Exp. Stn. Rept. 1889. p. 180.
- Theunissen, J. 1994.** Intercropping in field vegetable crops: Pest management by agrosystem diversification - an overview. Pestic. Sci. 42: 65-68.
- Theunissen, J., and H. Legutowska. 1991.** *Thrips tabaci* Lindeman (Thysanoptera: Thripidae) in leek: within-plant distribution. J. Appl. Entomol. 112: 309-316.
- Thind, T. S., and J. S. Jhooty. 1982.** Association of thrips with purple blotch infection on onions plants caused by *Alternaria porri*. Indian Phytopath. 35: 696-698.
- Toda, S., and M. Morishita. 2009.** Identification of three point mutations on the sodium channel gene in pyrethroid-resistant *Thrips tabaci* (Thysanoptera: Thripidae). J. Econ. Entomol. 102: 2296-3000.
- Triplehorn. C. A., and N. F. Johnson. 2005.** Borror and DeLong's introduction to the study of the insects. 7th edition. Thomson Brooks/Cole, Belmont, CA. 864 p.
- Uvah, I. I. I., and T. H. Coaker. 1984.** Effect of mixed cropping on some insect pests of carrots and onions. Entomol. Exp. Appl. 36: 159-167.
- Verma, S. K. 1966.** Studies on the host preference of the onion thrips, *Thrips tabaci* Lindeman to the varieties of onion. Indian J. Entomol. 28: 396-398.
- Vierbergen G., H. Kucharczyk, and W.D.J. Kirk. 2010.** A key to the second instar larvae of the Thripidae of the Western Palaearctic region (Thysanoptera). Tijdschr Entomol. 153: 99-160.
- Waiganjo, M. M., J. M. Mueke, and L. M. Gitonga. 2008.** Susceptible onion growth stages for selective and economic protection from onion thrips infestation, pp. 193-200 . In R. K Prange and S. D. Bishop (eds.), Proceedings,

Symposium: sustainability through integrated and organic horticulture.

International symposium of the International Society for Horticultural Science (ISHS), 13-19 August 2006, Seoul, Korea. Publication Acta Horticulturae.

767. International Society for Horticultural Science, Leuven, Belgium.

Waterhouse, D. F., and Norris. 1989. Biological control: Pacific prospects – Supplemental 1. Australian Centre for International Agricultural Research-ACIAR Monograph 12. 125 p.

Webster, F.M. 1901. The onion thrips, *Thrips tabaci* Lindem. Columbus Horticultural Society. Quarterly Journal of Proceedings. 16: 74-80.

Weiss, M. J., and R. J. Beshear. 1987. Seasonal distribution of the flower thrips (*Frankliniella tritici* (Fitch)) and onion thrips (*Thrips tabaci* Lindeman) (Thysanoptera: Thripidae) on safflower in eastern Montana. Can. Entomol. 119: 399-401.

Wilcox, J., and A. F. Howland. 1948. DDT Dust for control of onion thrips. J. Econ. Entomol. 41: 694-700.

Wogin, M. J., R. C. Butler, D. A. J. Teulon, and M. M. Davidson. 2010. Field response of onion thrips and New Zealand flower thrips to single and binary blends of thrips lures. Can. Entomol. 142: 75-79.

CHAPTER 2

Evaluation of Onion Cultivars for Resistance to Onion Thrips (Thysanoptera: Thripidae) and *Iris yellow spot virus*²

Abstract

Onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), a worldwide pest of onion, *Allium cepa* L., can reduce onion yield by >50% and be even more problematic when it transmits *Iris yellow spot virus* (IYSV). Because *T. tabaci* is difficult to control with insecticides and other strategies, field studies on onion resistance to *T. tabaci* and IYSV were conducted in 2007 and 2008 in two locations in New York State. Forty-nine cultivars were evaluated for resistance by counting the number of larvae weekly and recording leaf damage. In a separate experiment, the impact of *T. tabaci* and IYSV on plant growth and yield was examined by spraying half of the plants with an insecticide. Eleven of the 49 cultivars had very little leaf damage and were considered resistant to *T. tabaci*. Visual assessment indicated that all resistant cultivars had yellow-green colored foliage, whereas the other 38 had blue-green colored foliage. The visual assessment of color agreed with data on color taken with a HunterLab Ultra Scan XE colorimeter. The cultivars ‘Colorado 6’ and ‘NMSU 03-52-1’ had the lowest numbers of *T. tabaci*, suggesting strong antibiosis and/or antixenosis. The other nine cultivars had variable numbers of *T. tabaci* indicating a possible combination of categories of resistance. In the non-protected treatments there were significant reductions in plant height and plant weight in most of the resistant

² Diaz-Montano, J., M. Fuchs, B. A. Nault and A. M. Shelton. 2010. Evaluation of Onion Cultivars for Resistance to Onion Thrips (Thysanoptera: Thripidae) and Iris Yellow Spot Virus. J. Econ. Entomol. 103(3): 925-937.

cultivars, but there were reductions in bulb weight only in a few of them. The average of plants infected with IYSV was 10% in 2007 and 60% in 2008. Our findings indicate potential for developing onion resistance to *T. tabaci* as part of an overall IPM strategy, but suggest difficulties in identifying resistance to IYSV.

Resumen (Spanish)

El trips de la cebolla, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), una plaga a nivel mundial de la cebolla, *Allium cepa* L., causa pérdidas en rendimiento (>50%) y puede ser aun mas problemática cuando transmite *Iris yellow spot virus* (IYSV) causante de la mancha amarilla. Debido a que *T. tabaci* es difícil de controlar con insecticidas y otros métodos, estudios en campo sobre resistencia de la cebolla a *T. tabaci* se llevaron a cabo en 2007 y 2008 en dos lugares en el estado de Nueva York. Cuarenta y nueve genotipos fueron evaluados por medio de conteos de numero de larvas y evaluaciones del daño a la hoja. En otro experimento, se estimo el impacto de *T. tabaci* y el virus en el crecimiento de la planta y el rendimiento aplicando insecticida en la mitad de las plantas. Once de los 49 genotipos presentaron poco daño y fueron considerados resistentes a *T. tabaci*. Observaciones visuales indicaron que los genotipos resistentes tuvieron hojas de color verde-amarillo y los otros tuvieron hojas de color verde-azul, esto coincide con medidas de color tomadas con el “HunterLab Ultra Scan XE colorimeter.” ‘Colorado 6’ y ‘NMSU 03-52-1’ tuvieron los números mas bajos de *T. tabaci*, sugiriendo un alto nivel de antibiosis y/o antixenosis. Los otros nueve genotipos presentaron números variables de *T. tabaci* indicando una posible combinación de categorías de resistencia. Se observaron reducciones significativas en altura y peso de la planta en la mayoría de los genotipos resistentes, pero solo en unos pocos genotipos en el peso del bulbo. El promedio de plantas infectadas con IYSV fue

del 10% en el 2007 y del 60% en el 2008. Estos resultados indican un desarrollo potencial de resistencia de la cebolla a *T. tabaci* como táctica para el manejo integrado de esta plaga, pero revelan dificultades para identificar resistencia a IYSV.

Introduction

Onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), is a cosmopolitan and polyphagous pest, which probably originated from the eastern Mediterranean region, the center of origin for its most important host plant (onion, *Allium cepa* L.) (Mound 1997). *Thrips tabaci* is the main insect pest of onion in many parts of the world, including New York State where a total of 4,290 ha were planted in 2008 (NASS 2009). Several factors contribute to the high pest status of *T. tabaci*, including a rapid development time from egg to adult on onion, with reports ranging from 14.2 d (Arrieche et al. 2006) to 15.5 d (Murai 2000) at 23°C and 10.6 d at 30°C (Murai 2000). Its short generation time, coupled with its high reproductive capacity, frequently leads to population outbreaks, especially in hot, dry weather. *Thrips tabaci* feeding causes silvery leaf spots that turn into white blotches and silvery patches along the leaves, which reduces photosynthesis (Childers 1997). Its feeding can reduce onion bulb weight (Kendall and Capinera 1987, Rueda et al. 2007) resulting in yield losses of nearly 50% (Fournier et al. 1995) and 60% (Waiganjo et al. 2008).

Additionally *T. tabaci* transmits *Iris yellow spot virus* (IYSV) (family *Bunyaviridae*, genus *Tospovirus*). IYSV was first identified on onions in southern Brazil in 1981, prior to its first confirmation in the USA in 1989 in the Pacific Northwest (Gent et al. 2006). IYSV spread to several important onion producing states, including New York where it was confirmed in the summer of 2006 (Hoepting et al. 2007). IYSV symptoms on leaves appear as straw-colored to white, dry, and

sometimes as elongate lesions along the edges (Gent et al. 2006). Studies conducted in Colorado (Gent et al. 2004) indicate that IYSV reduces bulb size. Thus, besides the losses caused by direct feeding by *T. tabaci*, this virus poses a serious additional threat to onion production worldwide.

On onion, the main tactic used to manage *T. tabaci* infestations is the frequent use of foliar insecticides. This strategy is not sustainable for two main reasons. First, *T. tabaci* is difficult to control because insects are found mainly in the narrow spaces between the inner leaves (Shelton et al. 1987) where coverage with conventional foliar applied insecticides is difficult. Second, some populations of *T. tabaci* have developed resistance to pyrethroid and organophosphate insecticides in New York (Shelton et al. 2003, 2006) and Canada (MacIntyre Allen et al. 2005), as well as many other regions of the world (Martin et al. 2003, Herron et al. 2008, Morishita 2008).

Three categories of resistance describe the effects of host plant resistance (HPR) on insects: antibiosis, which adversely affects the biology of the insect; antixenosis, in which the plant is a poor host to the insect and affects its behavior; and tolerance, or ability of a plant to withstand or recover from insect damage (Smith 2005). HPR may offer a long-term solution to *T. tabaci* and IYSV control. This is especially true if adults avoid colonizing the plant because IYSV is acquired when early instars feed on infected plants and can be transmitted in a persistent fashion by second instars and adults (Gent et al. 2006). Plant characteristics that reduce plant attractiveness to *T. tabaci* adults may inhibit oviposition resulting in less larval feeding and development, and could play a vital role in reducing infection by IYSV.

The use of onion cultivars resistant to *T. tabaci* and IYSV would reduce insecticide usage, which would reduce environmental hazards and minimize the evolution of resistance to insecticides. Some studies on onion resistance to *T. tabaci* and IYSV have been conducted. Jones et al. (1935) compared *T. tabaci* populations on

46 onion cultivars. All cultivars tested had significantly higher numbers of *T. tabaci* than the resistant variety ‘White Persian’, which has thick, light green leaves and an open type of canopy. Coudriet et al. (1979) observed a similar type of leaf structure in the variety ‘Nebuka’, which had less *T. tabaci* when compared to three other onion cultivars. Loges et al. (2004) associated the low number of larvae found on the variety ‘Duquesa’ with the lowest number of leaves and largest angle between the central leaves, compared to seven other onion cultivars. In another study six of 61 genotypes screened for resistance sustained fewer *T. tabaci* than the other cultivars (Brar et al. 1993). For IYSV, du Toit and Pelter (2005) determined the response of 46 onion cultivars to IYSV and showed that all of them were susceptible to the virus with infection rates ranging from 58 to 97%.

While some progress has been made on HPR to *T. tabaci* and IYSV, more detailed studies are needed, especially because both pests are increasing in status worldwide (Gent et al. 2006). HPR is an important foundation of integrated pest management (IPM) (Panda and Khush 1995, Kennedy 2008). Evaluating a wide range of onion germplasm for resistance to *T. tabaci* and IYSV is critical for advancing the potential of using host plant resistance in onion IPM. The major objective of our study was to find new sources of resistance to both *T. tabaci* and IYSV by screening existing commercial lines and advanced breeding lines. Onion cultivars were evaluated in replicated field experiments in which *T. tabaci* populations and IYSV incidence were recorded over time. Additionally, the impact that *T. tabaci* and/or IYSV had on growth and bulb yield was determined.

Materials and Methods

Plant Material

In this study a total of 49 dry bulb onion cultivars (Table 2.1) were used. Cultivars were selected based on their suspected resistance or susceptibility to *T. tabaci*. Additionally, cultivars popular with New York and Northeast growers were included. This information was obtained by personal communication with New York extension educators, onion researchers at Colorado State University, New Mexico State University, University of Wisconsin and onion seed companies. The cultivar ‘Nebula’ was used as the susceptible check in all the experiments not only for its susceptibility to *T. tabaci* but also for being one of the most popular onion cultivars grown in New York. Information on days to maturity and bulb color was obtained from the respective companies or the breeder.

Screening Cultivars for *T. tabaci* Populations and Their Damage on Plant Leaves

In 2007 and 2008, 22 and 46 onion cultivars, respectively, were evaluated for resistance to *T. tabaci*, or *T. tabaci*/IYSV using *T. tabaci* counts, and plant damage ratings. Plants were seeded into 200 cell 4.5 cm plug trays with one seed per cell filled with Cornell mix soil (Boodley and Sheldrake 1977), and then grown under greenhouse conditions at 20-30°C and 20-40% RH with supplemental lights set for a period of 14:10 (L:D) h. After eight wk in the greenhouse, onion plants were transplanted into a commercial field in 2007 (Potter, NY) and two commercial fields in 2008 (Potter, NY and Elba, NY) in a randomized complete block design consisting of four blocks, each block with 20 plants per cultivar in a row. Distance between plant rows was 30 cm, and distance between plants within rows was 5 cm.

Table 2.1. List of onion cultivars used in this study

Cultivar	Leaf color ^a	Hunter 'b' values (mean \pm SE) ^b	Response to <i>T. tabaci</i> ^c	Days to maturity	Seed company
OLYS05N5 ¹	Yellow-green	18.4 \pm 1.5a	Resistant	120	Crookham
Tioga ¹	Yellow-green	18.4 \pm 1.3a	Resistant	118	Seminis
Peso ¹	Yellow-green	17.8 \pm 2.2ab	Resistant	115	Bejo
Calibra ¹	Yellow-green	17.7 \pm 2.3ab	Resistant	115	Bejo
Damascus ¹	Blue-green	17.6 \pm 3.2ab	Susceptible	112	Seminis
Vaquero ¹	Yellow-green	16.9 \pm 2.0a-c	Resistant	118	Nunhems
Candy ¹	Blue-green	16.8 \pm 2.5a-c	Susceptible	95	Seminis
Cometa ²	Yellow-green	16.4 \pm 1.8a-d	Resistant	120	Nunhems
Medeo ¹	Yellow-green	16.4 \pm 3.6a-d	Resistant	106	Bejo
SYN-G2 ¹	Blue-green	16.3 \pm 2.1a-e	Susceptible	N/A	d
NMSU 03-52-1 ¹	Yellow-green	16.1 \pm 1.1a-f	Resistant	120	e
Delgado ¹	Yellow-green	15.2 \pm 2.3a-f	Resistant	116	Bejo
Festival ¹	Blue-green	15.1 \pm 2.0a-g	Susceptible	108	Bejo
T-433 ¹	Yellow-green	15.1 \pm 1.7a-g	Resistant	117	Takii
Colorado 6 ¹	Yellow-green	15.0 \pm 2.4a-g	Resistant	120	Crookham
602-1 ¹	Blue-green	14.7 \pm 1.2a-g	Susceptible	N/A	f
Yankee ¹	Blue-green	14.4 \pm 2.2a-g	Susceptible	108	Bejo
601-1 ¹	Blue-green	14.2 \pm 3.3a-g	Susceptible	N/A	f
Verrazano ¹	Blue-green	14.1 \pm 3.1a-g	Susceptible	110	Seminis
606-1 ¹	Blue-green	13.8 \pm 2.0a-g	Susceptible	N/A	f
SYN-H10 ¹	Blue-green	13.8 \pm 2.8a-g	Susceptible	N/A	d
Red Bull ³	Blue-green	13.7 \pm 2.2a-g	Susceptible	117	Bejo
Red Zeppelin ³	Blue-green	13.6 \pm 1.9a-g	Susceptible	115	Seminis
SYN-G1 ¹	Blue-green	13.6 \pm 3.1a-g	Susceptible	N/A	d
406-1 ¹	Blue-green	13.4 \pm 1.3a-g	Susceptible	N/A	f
Bastille ¹	Blue-green	13.1 \pm 1.4a-g	Susceptible	100	Stokes
SYN-H7 ¹	Blue-green	13.1 \pm 0.9a-g	Susceptible	N/A	d
Santana ¹	Blue-green	12.9 \pm 1.5b-g	Susceptible	115	Bejo
Barrage ¹	Blue-green	12.7 \pm 2.8b-g	Susceptible	100	Stokes
Frontier ¹	Blue-green	12.7 \pm 1.5b-g	Susceptible	100	Takii
Sherman ¹	Blue-green	12.6 \pm 1.9b-g	Susceptible	100	Bejo
Corona ¹	Blue-green	12.5 \pm 2.3b-g	Susceptible	100	Bejo
Milestone ¹	Blue-green	12.2 \pm 2.1c-g	Susceptible	110	Takii
Nicolet ¹	Blue-green	12.1 \pm 1.8c-g	Susceptible	112	Seminis
Joliet ¹	Blue-green	12.0 \pm 1.3c-g	Susceptible	105	Seminis
Mountaineer ¹	Blue-green	12.0 \pm 1.1c-g	Susceptible	100	Takii
Nebula ¹	Blue-green	11.8 \pm 2.4c-g	Susceptible	100	Nunhems
Red Wing ³	Blue-green	11.8 \pm 1.4c-g	Susceptible	118	Bejo
Ruby Ring ³	Blue-green	11.7 \pm 1.8c-g	Susceptible	112	Takii
Infinity ¹	Blue-green	11.6 \pm 2.5c-g	Susceptible	105	Nunhems
Tahoe ¹	Blue-green	11.6 \pm 2.4c-g	Susceptible	102	Bejo
Red Beauty ³	Blue-green	11.3 \pm 2.2d-g	Susceptible	105	Bejo
Mars ³	Blue-green	11.1 \pm 0.7d-g	Susceptible	108	Seminis

Table 2.1 (Continued)

Trailblazer ¹	Blue-green	10.9 ± 1.7e-g	Susceptible	100	Takii
Alonso ¹	Blue-green	10.8 ± 2.2f-g	Susceptible	106	Bejo
Prince ¹	Blue-green	9.8 ± 1.5g	Susceptible	105	Bejo
Bunker ¹	Blue-green	N/A	Susceptible	120	Seminis
Fortress ¹	Blue-green	N/A	Susceptible	110	Seminis
Millennium ¹	Blue-green	N/A	Susceptible	105	Nunhems

^{1, 2, 3} Bulb color. 1: yellow, 2: white and 3: red.

^a Leaf color obtained by personal observation.

^b Leaf color taken by using a HunterLab Ultra Scan XE colorimeter. +b indicates yellow, -b indicates blue.

^c Onion cultivars confirmed or found as resistant or susceptible in this study.

^d Onion lines developed in the program of M.A. Mutschler. Department of Plant Breeding and Genetics, Cornell University, Ithaca, NY.

^e Onion line developed in the program of C.S. Cramer. Department of Plant and Environmental Science, New Mexico State University, Las Cruces, NM.

^f Onion lines developed in the program of M. Havey. USDA-ARS and Department of Horticulture, University of Wisconsin, Madison, WI.

Within a column, means followed by different letters are significantly different ($P < 0.05$, Tukey's test)

The number of *T. tabaci* larvae was counted in a non-destructive fashion from 7 randomly selected plants per cultivar in each block. Counts started after the first *T. tabaci* were observed (31-VII-2007 and 14-VII-2008, respectively) and continued every 7 d until plants reached maturity or until one of the cultivars was completely damaged so it could no longer serve as a host.

A visual rating for leaf damage caused by *T. tabaci* was taken once during the season using a scale ranging from 1 to 9. Similar scales (9-point) have been used to measure damage caused by different insect pests on different crops (Coudriet et al. 1979, Smith 2005). In this study, a rating of 1 = no damage; 3 = 25% of the leaves white or with blotches; 5 = 50% of leaves white or with blotches; 7 = 75% of leaves white or with blotches; and 9 = complete damage (100% leaves white). The senior author estimated the ratings visually.

Information on leaf color was obtained by personal observation on 49 onion cultivars. Leaf color was also measured on 46 onion cultivars using the HunterLab Ultra Scan XE colorimeter (Hunter Associates Laboratory, Reston, VA). The HunterLab Colorimeter responded to spectral distributions of light in the same manner as the human eye. It takes direct readings of 'a', 'b', and 'L'. The 'L' measures from black (0) to white (100), +b measures yellow, -b blue, +a red, and -a green color (Ameny and Willson 1997). Only Hunter 'b' values were taken into account for this study because the leaf color of the onion cultivars evaluated varied from blue-green to yellow-green (+b indicates yellow, -b indicates blue). Five outer leaves per plant were selected in the field and measurements were taken on the outside and inside middle section of each leaf and the mean of the two measurements was used.

Impact of *T. tabaci* Populations on Leaves, Plant Growth and Bulb Yield

The impact of *T. tabaci* and *T. tabaci*/YYSV on onion plant growth (2007) and bulb yield (2008) was evaluated with seven and 12 onion cultivars, respectively. Plants were grown in the greenhouse as described above. After eight wk in the greenhouse, the cultivars were transplanted into a field in 2007 (Potter, NY) and three field locations in 2008 (Potter, Elba I, and Elba II) in a split plot design with four blocks, and two treatments per block, one protected (P) with insecticide and the other nonprotected (NP). There were 20 plants per cultivar in each treatment per block. Distance between plant rows was 30 cm, and distance between plants within rows was 5 cm.

The number of *T. tabaci* larvae was counted weekly, as in the screening experiment, from 10 randomly selected plants per replicate. The insecticide spinetoram (Radiant SC, Dow AgroSciences, Indianapolis, IN) was sprayed in the protected treatment immediately after every count using a backpack CO₂ sprayer with

four nozzles, two inside (XR8004VS) and two outside (XR11004VS), at 2.7 atm. The rate of the insecticide was 0.58 L/ha and the volume was 746.0 L/ha. Visual ratings for leaf damage caused by *T. tabaci* were recorded using the scale described above.

In 2007, height and fresh weight of plants were measured on eight plants per cultivar in each replicate. In 2008, plant height and weight of bulbs at harvest were taken on five and seven plants, respectively, per cultivar in each replicate. Weight of bulbs in 2007 was not taken because onions were transplanted into the field late (end of June), which did not allow the bulbs to fully mature.

IYSV Infection Assessment

Onions infected with IYSV may or may not express symptoms (BAN pers. obs.). Therefore, onion plants infected with IYSV were diagnosed using double antibody sandwich enzyme-linked immunosorbent assays (DAS-ELISA) (Clark and Adams 1977) and commercially available antibodies, as well as positive and negative controls for IYSV (Agdia Inc., Elkhart, IN). At the end of the 2007 season, all the plants in the field were taken to the laboratory and tested for IYSV. Plants were tested individually; a section of leaf tissue from the middle section of the plant was used where preliminary studies have shown a greater probability of detecting the virus (BAN unpublished). All samples and controls were tested in duplicate wells on 96-well microtiter plates and the mean of the two readings was used for data analysis. At the end of the 2008 season, seven plants per cultivar per replicate were taken to the laboratory to determine the presence of IYSV by DAS-ELISA. In some cases there were less than seven plants per cultivar available due to dryness or early maturation. Plants in Elba II were not tested.

Statistical Analyses

Analysis of variance (ANOVA) for *T. tabaci* populations, leaf damage ratings, plant height, plant fresh weight, bulb weight and color data among cultivars was conducted by using PROC GLM and controlled for blocks. Multiple comparisons were computed by using Tukey's studentized range test ($P < 0.05$) (SAS Institute 2003). For the experiments with P and NP treatments each cultivar was analyzed separately because our interest was to compare *T. tabaci* populations, leaf damage ratings, plant height, plant fresh weight and bulb weight between these treatments. Data were then analyzed as a randomized complete block design using PROC GLM. Subsequently, separate analyses were conducted to compare responses of cultivars to these factors within P and NP treatments, also using a randomized complete block design.

A logistic regression model for IYSV infection rates was performed by using PROC GENMOD and controlled for blocks (SAS Institute 2003). In the case of the experiments with P and NP treatments, each cultivar was analyzed separately because the interest was to compare IYSV infection rates between the two treatments.

Analysis of regression was done (PROC REG) with days to maturity, Hunter 'b' values and cumulative number of *T. tabaci* larvae as predictors of onion leaf damage caused by *T. tabaci* ($Y_{\text{damage}} = \text{days to maturity} + \text{Hunter 'b' values} + \text{cumulative number of } T. \text{ tabaci larvae}$) and as well as predictors of IYSV ($Y_{\text{IYSV}} = \text{days to maturity} + \text{Hunter 'b' values} + \text{cumulative number of } T. \text{ tabaci larvae}$) (SAS Institute 2003). Correlation coefficients (r) were calculated by examining the relationship between *T. tabaci* populations, damage, days to maturity and IYSV percentage of plants infected in the screening experiments.

Results

Screening Cultivars for *T. tabaci* Populations and Their Damage on Plant Leaves

Damage on Plant Leaves. In 2007, visual rating for *T. tabaci* leaf damage was done at 89 d after transplanting (DAT). There were significant differences among cultivars ($F = 12.45$; $df = 21, 63$; $P < 0.001$) (Table 2.2). Of the 22 cultivars, 14 had damage ratings between 3.4 and 4.4 with 30 and 43% of their leaf tissue damaged by *T. tabaci*. The cultivar ‘OLYS05N5’ had the lowest damage (<10% leaf damage) and was significantly less damaged than many of the popular commercial cultivars (e.g. ‘Infinity’, ‘Red Wing’, ‘Nebula’, ‘Red Bull’, ‘Red Beauty’) and had similar ratings to ‘Peso’, ‘Colorado 6’, ‘Cometa’, ‘Tioga’, ‘Delgado’, ‘Calibra’ and ‘Medeo’ (Table 2.2). In 2008, *T. tabaci* caused limited leaf damage in Potter with only ca. 20% in the most susceptible cultivars (Table 2.2). In Elba, leaf damage was evaluated at 87 DAT and was ca. 70% in the susceptible cultivar ‘Infinity’. The reaction of the resistant cultivars ‘OLYS05N5’, ‘Colorado 6’, ‘T-433’, NMSU 03-52-1, ‘Delgado’, ‘Peso’, ‘Tioga’, ‘Cometa’, ‘Medeo’, ‘Calibra’ and ‘Vaquero’ was significantly ($F = 10.09$; $df = 45, 135$; $P < 0.001$) different from ‘Infinity’ (Table 2.2).

Table 2.2. Ratings of onion leaf damage (mean \pm SE) due to *T. tabaci* (Screening experiments) in Potter (2007, 22 onion cultivars) at 89 DAT, Potter (2008, 46 cultivars) at 87 DAT and Elba (2008, 46 cultivars) at 87 DAT

Cultivar	Potter (2007) ^a	Potter (2008) ^a	Elba (2008) ^a
OLYS05N5	1.6 \pm 0.5e	1.0 \pm 0.0c	1.0 \pm 0.0g
Colorado 6	2.0 \pm 0.4e	1.0 \pm 0.0c	1.1 \pm 0.3g
T-433		1.0 \pm 0.0c	1.6 \pm 0.3fg
NMSU 03-52-1		1.1 \pm 0.3bc	1.6 \pm 0.6fg
Delgado	2.4 \pm 0.5c-e	1.0 \pm 0.0c	1.8 \pm 0.3fg
Peso	1.9 \pm 0.3e	1.0 \pm 0.0c	1.9 \pm 0.3d-g
Tioga	2.4 \pm 0.5c-e	1.1 \pm 0.3bc	1.9 \pm 0.5d-g
Cometa	2.3 \pm 0.6de	1.0 \pm 0.0c	2.1 \pm 0.9c-g
Medeo	2.8 \pm 0.3b-e	1.0 \pm 0.0c	2.3 \pm 0.5b-g
Calibra	2.4 \pm 0.6c-e	1.1 \pm 0.3bc	2.3 \pm 0.5b-g
Vaquero		1.0 \pm 0.0c	2.3 \pm 1.0b-g
Mountaineer		1.9 \pm 0.3ab	3.6 \pm 0.5a-g
Ruby Ring		2.0 \pm 0.4a	3.6 \pm 0.5a-g
SYN-G2		2.0 \pm 0.0a	4.0 \pm 0.8a-f
Trailblazer		2.1 \pm 0.3a	4.1 \pm 1.9a-f
SYN-G1		2.1 \pm 0.3a	4.3 \pm 0.6a-f
406-1		1.9 \pm 0.3ab	4.3 \pm 1.3a-f
Damascus		1.8 \pm 0.3a-c	4.3 \pm 1.4a-f
Verrazano		2.3 \pm 0.5a	4.4 \pm 1.3a-f
602-1		1.8 \pm 0.3a-c	4.4 \pm 1.8a-f
Candy		2.3 \pm 0.3a	4.5 \pm 0.6a-e
Frontier		2.3 \pm 0.2a	4.5 \pm 1.0a-e
Alonso	4.0 \pm 0.4ab	2.1 \pm 0.3a	4.5 \pm 1.7a-e
Mars		2.1 \pm 0.3a	4.6 \pm 1.3a-d
601-1		2.4 \pm 0.5a	4.6 \pm 1.7a-d
Nicolet		2.1 \pm 0.3a	4.8 \pm 1.0a-c
Red Zeppelin		2.3 \pm 0.6a	4.8 \pm 1.3a-c
SYN-H10		2.1 \pm 0.3a	4.8 \pm 1.3a-c
Milestone	3.9 \pm 0.9ab	2.0 \pm 0.4a	5.0 \pm 0.7ab
Sherman		2.0 \pm 0.4a	5.0 \pm 1.4ab
SYN-H7	3.5 \pm 0.4a-d	1.9 \pm 0.3ab	5.0 \pm 1.6ab
Barrage		2.1 \pm 0.3a	5.1 \pm 1.8a
606-1	3.4 \pm 0.5a-d	2.1 \pm 0.3a	5.1 \pm 2.2a
Joliet		2.0 \pm 0.0a	5.3 \pm 1.7a
Yankee	4.1 \pm 0.9a	2.1 \pm 0.6a	5.4 \pm 0.5a
Red Beauty	4.4 \pm 0.5a	1.9 \pm 0.3ab	5.4 \pm 1.1a
Santana	4.0 \pm 0.4ab	2.1 \pm 0.3a	5.5 \pm 1.0a
Festival		2.1 \pm 0.3a	5.5 \pm 1.3a
Prince		2.1 \pm 0.3a	5.5 \pm 1.3a

Table 2.2 (Continued)

Red Bull	4.0 ± 1.1ab	1.9 ± 0.3ab	5.8 ± 1.0a
Bastille		1.9 ± 0.3ab	5.9 ± 0.3a
Tahoe		2.1 ± 0.3a	5.9 ± 0.3a
Corona		2.3 ± 0.3a	6.0 ± 0.8a
Nebula	3.9 ± 0.8ab	2.3 ± 0.5a	6.0 ± 0.8a
Red Wing	4.1 ± 0.5a	2.3 ± 0.3a	6.1 ± 0.6a
Infinity	4.0 ± 0.7ab	2.1 ± 0.5a	6.3 ± 1.0a
Bunker	3.5 ± 0.0a-d		
Fortress	3.8 ± 0.3ab		
Millenium	3.6 ± 0.3a-c		

^a Visual rating for *T. tabaci* leaf damage on a scale ranging from 1 to 9. 1 = no damage; 3 = 25% of the leaves white or with blotches; 5 = 50% of leaves white or with blotches; 7 = 75% of leaves white or with blotches; and 9 = complete damage (100% leaves white).

Within a column, means followed by different letters are significantly different ($P < 0.05$, Tukey's test)

Thrips tabaci Populations. In 2007, the first count of *T. tabaci* larvae was done at 34 DAT and then every seven d until 105 DAT for a total of 11 counts. Figure 2.1 illustrates the cumulative number of larvae on the eight cultivars that had the lowest damage rating (Table 2.2). Cultivars 'Nebula' and 'Yankee' were used as susceptible checks. There were significant differences in the cumulative number of larvae among cultivars at 90 DAT ($F = 15.06$; $df = 9, 267$; $P < 0.001$) and 105 DAT ($F = 20.41$; $df = 9, 267$; $P < 0.001$) (Figure 2.1). The cultivar 'Colorado 6' had the lowest number of larvae but was not significantly different from 'OLYS05N5', 'Cometa', or 'Tioga' at 90 DAT and 105 DAT (Figure 2.1).

In 2008, the first count of *T. tabaci* larvae was done at 44 DAT and then every seven d until 86 DAT for a total of seven counts. Populations of *T. tabaci* in Potter were very low (data not shown) but *T. tabaci* larvae populations in Elba were higher (data not shown) causing leaf damage >70%, as explained above.

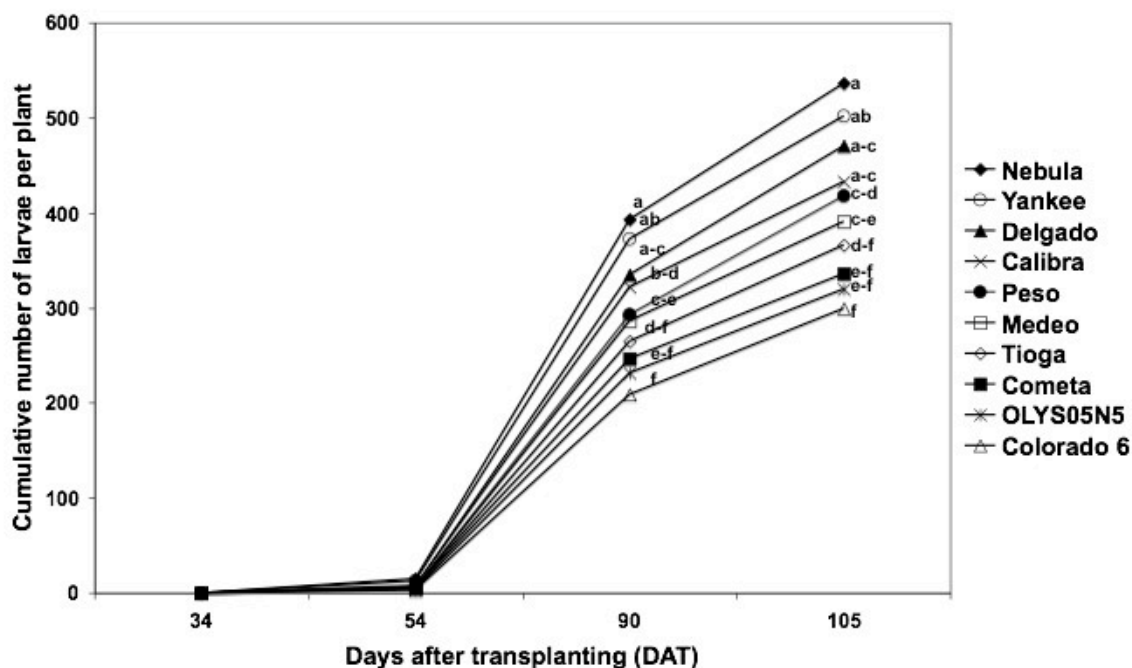


Figure. 2.1. Cumulative number of larvae per plant on 10 onion cultivars (Screening experiment, 2007). Lines with different letters are significantly different ($P < 0.05$, Tukey's test).

IYSV Infection Assessment. In 2007, all the plants present at the end of the experiment were collected; there were between 23 and 43 plants per cultivar for a total of 678 onion plants. Only 11% of the plants were infected with IYSV. The percentage of plants infected ranged from 3 to 31% (Table 2.3) and there were no significant ($\chi^2 = 27.67$; $df = 21$; $P = 0.1498$) differences in infection levels among the cultivars tested. The eight cultivars that had the lowest leaf rating damage (Table 2.2) had infection rates below or close to 10%, except for 'Delgado', which had an IYSV infection rate of 19%. The cultivar 'Infinity', which had one of the highest damage ratings and numbers of larvae, had only one infected plant (3%) (Table 2.3).

In 2008, 20-28 plants were tested per cultivar in Potter, making a total of 1,135 plants (Table 3). Percentages of plants infected with IYSV varied from 16 to 75% and there were significant differences ($\chi^2 = 118.37$; $df = 40$; $P < 0.001$) in infection rates

among cultivars. The cultivar ‘Santana’ had the highest infection rate (75%) and was not significantly different from the cultivars ‘Red Zeppelin’, ‘Red Wing’, ‘Sherman’, ‘Red Bull’, ‘Calibra’, SYN-H10, ‘Medeo’, and ‘Nicolet’ (Table 2.3). In Elba, a total of 1,099 plants were tested and most of the cultivars listed had 28 plants tested except for ‘Nebula’, ‘SYN-H10’, ‘Barrage’, ‘406-1’, ‘601-1’, ‘Red Wing’, ‘Damascus’, ‘Bastille’, and ‘Vaquero’ that had between 23 and 27 plants. The number of plants tested on the cultivars ‘Mountaineer’, ‘Corona’, ‘Festival’, ‘Santana’, ‘Frontier’, and ‘606-1’ ranged from 13 to 19. Percentages of plants infected varied from 15 to 79% and there were significant ($\chi^2 = 93.21$; $df = 42$; $P < 0.001$) differences in infection levels among cultivars (Table 2.3). The highest infection percentage in the cultivar ‘Red Zeppelin’ (79%) was not different from ‘Santana’, ‘Calibra’, ‘Red Bull’, ‘Infinity’, ‘406-1’ and ‘Delgado’ (Table 2.3).

Table 2.3. IYSV incidence on onion plants, as shown by DAS-ELISA, in the screening experiments in Potter, 2007 (22 onion cultivars), Potter, 2008 (41 cultivars) and Elba, 2008 (43 cultivars)

Cultivar	Potter 2007 % plants infected (mean \pm SE)	Potter 2008 % plants infected (mean \pm SE)	Elba 2008 % plants infected (mean \pm SE)
Vaquero		50.0 \pm 24.7b-e	14.8 \pm 11.2h
606-1	31.0 \pm 53.2a	17.9 \pm 27.0hi	15.8 \pm 18.7gh
Yankee	16.7 \pm 19.2a	21.5 \pm 8.3g-i	21.5 \pm 7.6gh
Bastille		39.3 \pm 29.4c-h	24.0 \pm 25.7gh
SYN-G2		35.7 \pm 37.8c-h	25.0 \pm 12.7f-h
OLYS05N5	8.8 \pm 17.7a	25.0 \pm 24.4f-i	25.0 \pm 16.7f-h
Damascus		42.9 \pm 35.0b-g	25.0 \pm 19.9f-h
Milestone	3.2 \pm 6.5a	46.4 \pm 24.4b-f	28.6 \pm 10.8e-h
SYN-H7	15.4 \pm 21.8a	39.3 \pm 18.0c-h	28.6 \pm 10.8e-h
Corona		42.9 \pm 23.3b-g	28.6 \pm 30.5 e-h
Mountaineer			30.8 \pm 23.2e-h
T-433		28.6 \pm 26.1d-i	32.2 \pm 12.7e-h
Sherman		60.7 \pm 29.4a-c	32.2 \pm 16.6e-h
Cometa	2.7 \pm 5.4a	17.9 \pm 18.0hi	32.2 \pm 22.6e-h
Barrage		25.0 \pm 24.4f-i	34.8 \pm 26.3d-h

Table 2.3 (Continued)

Mars		17.9 ± 13.7hi	35.7 ± 22.9d-h
Colorado 6	10.7 ± 21.5a	32.2 ± 21.4d-i	35.7 ± 25.3d-h
Verrazano		25.0 ± 13.7f-i	35.7 ± 31.5d-h
Alonso	11.1 ± 22.2a	25.0 ± 24.4f-i	35.8 ± 7.6d-h
SYN-G1		28.6 ± 11.7d-i	36.0 ± 25.3d-h
Frontier			36.9 ± 43.2d-h
Tahoe		25.6 ± 31.4e-i	37.0 ± 13.7d-h
601-1			38.5 ± 24.6c-h
Ruby Ring		27.0 ± 30.8d-i	39.3 ± 22.6c-g
Festival		39.3 ± 21.4c-h	41.2 ± 32.7b-g
Joliet		32.1 ± 29.4d-i	42.3 ± 31.6b-g
Prince		39.3 ± 13.6c-h	42.9 ± 10.8b-g
Tioga	4.4 ± 8.7a	25.0 ± 21.5f-i	42.9 ± 10.8b-g
NMSU 03-52-1		39.3 ± 21.4c-h	42.9 ± 15.2b-g
602-1		32.2 ± 13.7d-i	42.9 ± 20.2b-g
Peso	8.3 ± 5.6a	35.7 ± 18.4c-h	42.9 ± 28.6b-g
Medeo	8.0 ± 16.0a	53.6 ± 7.1a-d	46.4 ± 12.6b-g
SYN-H10		53.6 ± 13.6a-d	47.9 ± 15.4b-g
Nebula	11.6 ± 14.0a	28.6 ± 30.8d-i	47.9 ± 20.3b-f
Nicolet		53.6 ± 13.6a-d	50.0 ± 13.2b-f
Red Wing	13.8 ± 19.5a	67.9 ± 27.0ab	52.0 ± 22.2b-e
Delgado	18.6 ± 15.2a	46.5 ± 17.9b-f	53.6 ± 16.6a-e
406-1		46.4 ± 24.4b-f	60.0 ± 32.8a-d
Infinity	3.0 ± 6.1a	35.7 ± 24.7c-h	60.7 ± 29.3a-d
Red Bull	19.3 ± 19.4a	60.7 ± 18.0a-c	64.3 ± 17.1a-c
Calibra	9.7 ± 12.4a	53.6 ± 29.4a-d	67.8 ± 12.7ab
Santana	12.9 ± 14.9a	75.0 ± 24.4a	72.2 ± 19.7ab
Red Zeppelin		67.9 ± 21.4ab	78.6 ± 17.1a
Red Beauty	5.9 ± 6.8a	16.1 ± 23.6i	
Bunker	12.0 ± 24.0a		
Fortress	8.0 ± 9.2a		
Millenium	19.3 ± 14.7a		
No. plants			
tested	678	1135	1099
Avg % infected	10.8	38.4	41.1

Within a column, means followed by different letters are significantly different ($\alpha = 0.05$, Logistic regression model using PROC GENMOD)

Measurement of Onion Leaf Color. Leaf color was visually assessed and there were two colors observed among the different cultivars, yellow-green and blue-green (Table 2.1). All the Hunter 'b' values were positive indicating a dominance of yellow color over blue color (Table 2.1). Only the cultivars that showed resistance to *T. tabaci* had yellow-green leaf color (Table 2.1) and along with the other four cultivars had the highest b values (Table 2.1). Figure 2.2A clearly shows that the resistant varieties on the upper-left corner were the only ones with both, low damage and high 'b' values.

Relationship Between Damage on Plant Leaves, T. tabaci Populations, IYSV, Days to Maturity and Hunter 'b' Values. The correlation coefficients (r) between damage and cumulative number of larvae were not very strong in the screening experiments in Potter (2007), Potter (2008) and Elba (2008) with values of 0.57, 0.72 and 0.70, respectively (Table 2.4). However, correlation between damage ratings within the different locations was very strong with values of 0.93 (Potter 2007 and 2008), 0.96 (Potter 2007 and Elba 2008), and 0.89 (Potter 2008 and Elba 2008). There was very low correlation between IYSV percentage of plants infected and damage ratings in Potter 2007, Potter 2008 and Elba 2008 (0.15, 0.08 and 0.13, respectively); between IYSV percentage of plants infected and cumulative number of larvae in Potter 2007, Potter 2008 and Elba 2008 (0.27, 0.05 and 0.05, respectively); and between IYSV percentage of plants infected within the different locations, 0.15 (Potter 2007 and 2008), -0.14 (Potter 2007 and Elba 2008), and 0.60 (Potter 2008 and Elba 2008) (Table 2.4). The correlation between days to maturity and plant leaf damage was not very strong in Potter (2007), Potter (2008) and Elba (2008), -0.57, -0.65 and -0.60, respectively. Correlation was low between days to maturity and cumulative number of larvae in Potter (2007), Potter (2008) and Elba (2008), -0.65, -0.43 and -0.44, respectively. The correlation between days to maturity and IYSV percentage of

plants infected was very low in Potter (2007), Potter (2008) and Elba (2008), -0.03, 0.15 and 0.14, respectively (Table 2.4).

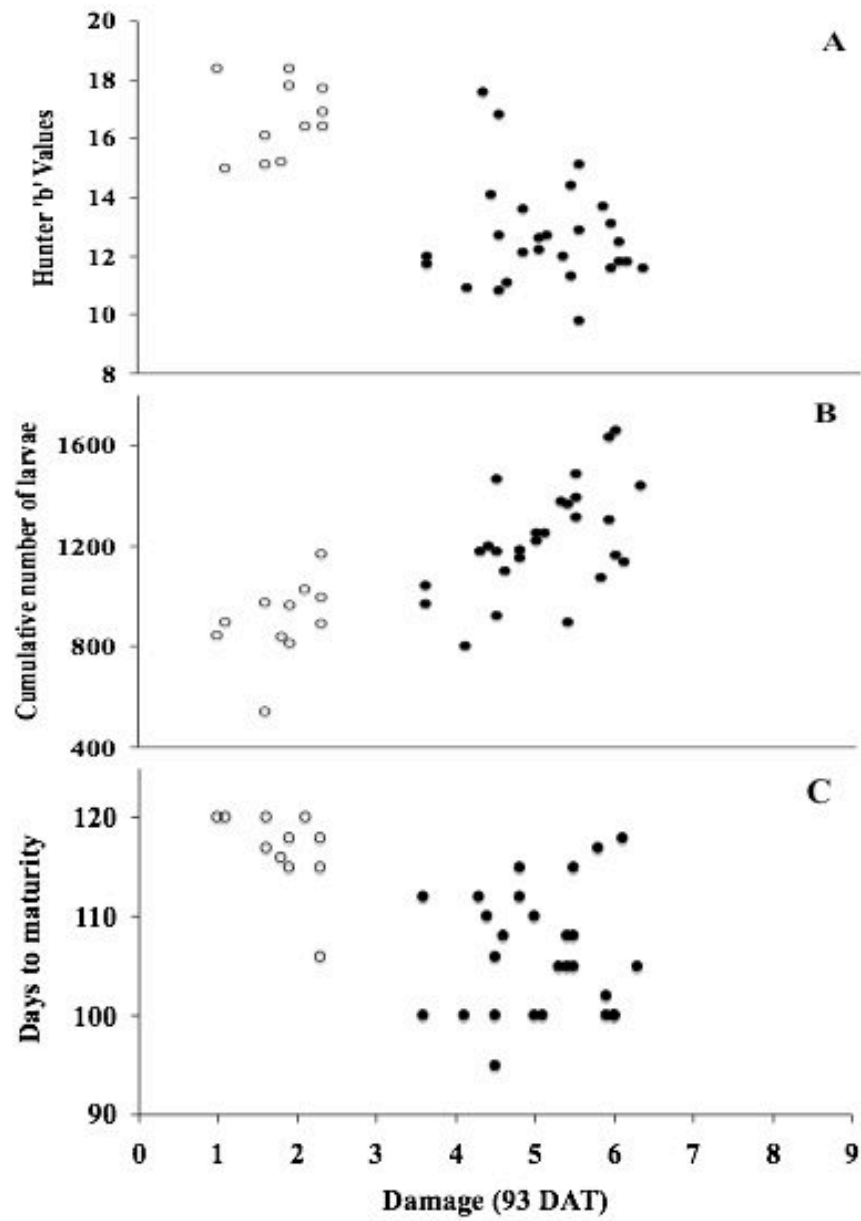
Days to maturity, Hunter 'b' values and cumulative number of *T. tabaci* were used to predict leaf damage caused by *T. tabaci* and IYSV infection in the screening experiment in 2008. Hunter 'b' values ($F = 9.62$; $df = 37$; $P < 0.0039$) (Figure 2.2A) and cumulative number of *T. tabaci* ($F = 15.87$; $df = 37$; $P < 0.0003$) (Figure 2.2B) were significant predictors of leaf damage. Days to maturity approached significance ($F = 3.93$; $df = 37$; $P < 0.0556$) as a predictor of damage (Figure 2.2C). However, Hunter 'b' values ($F = 1.26$; $df = 34$; $P < 0.2707$), cumulative number of *T. tabaci* ($F = 0.49$; $df = 34$; $P < 0.4905$) and days to maturity ($F = 2.91$; $df = 34$; $P < 0.0979$) were not significant predictors of IYSV percentage of plants infected.

Table 2.4. Correlation coefficients [r] between leaf damage ratings, cumulative number of *T. tabaci* larvae, IYSV percentage of plants infected and days to maturity in the screening experiments

	Potter 2007			Potter 2008			Elba 2008		
	Damage	Cumulative	IYSV	Damage	Cumulative	IYSV	Damage	Cumulative	IYSV
Damage rating (Potter 2007)		0.57(22)	0.15(19)	0.93(19)			0.96(19)		
Damage rating (Potter 2008)					0.72(46)	0.08(41)	0.89(46)		
Damage rating (Elba 2008)								0.70(46)	0.13(43)
IYSV (%) (Potter 2007)		0.27(19)				0.15(19)			-0.14(18)
IYSV (%) (Potter 2008)					0.05(41)				0.60(40)
IYSV (%) (Elba 2008)								0.05(43)	
Days to maturity	-0.57(20)	-0.65(20)	-0.03(20)	-0.65(38)	-0.43(38)	0.15(33)	-0.60(38)	-0.44(38)	0.14(33)

The value in parenthesis indicates the number of different onion cultivars used for each correlation

Figure 2.2. Hunter ‘b’ values, cumulative number of larvae, and days to maturity as predictors of leaf damage (Yield loss experiment, 2008). A. Damage vs. Hunter ‘b’ values; B. Damage vs. cumulative number of larvae; C. Damage vs. days to maturity. Hunter ‘b’ values ($P < 0.0039$) and cumulative number of *T. tabaci* ($P < 0.0003$) were significant predictors of leaf damage. Days to maturity approached significance ($P < 0.0556$) as a predictor of damage ($P < 0.05$, Regression analyses using PROC REG). Unfilled circles represent the 11 onion cultivars found resistant to *T. tabaci*.



Impact of *T. tabaci* Populations on Leaves, Plant Growth and Bulb Yield

Damage on Plant Leaves. In 2007, the leaf damage evaluation was done at 89 DAT. There were significant ($F = 28.84$; $df = 6, 18$; $P < 0.001$) differences in leaf damage ratings among cultivars in the nonprotected (NP) treatment (Table 2.5). As in the screening experiment, the cultivar ‘OLYS05N5’ had the lowest damage rating in the NP treatment but was not significantly different from ‘Colorado 6’ or ‘Peso’ (Table 2.5); and the leaf damage observed in the cultivar ‘Delgado’ was not significantly different from ‘Colorado 6’ or ‘Peso’. As expected, the insecticide used was very effective and kept *T. tabaci* populations extremely low throughout the experiment with the cultivars in the protected (P) treatment having 0% (damage rating=1) leaf damage (Table 2.5).

In 2008, populations of *T. tabaci* larvae in Elba I were higher than in the other two locations and the damage in the susceptible check, ‘Nebula’, was ca. 70% in the NP treatment (Table 2.5). The damage in the cultivars ‘Cometa’, ‘Vaquero’, ‘Colorado 6’, ‘OLYS05N5’, ‘T-433’ and ‘NMSU 03-52-1’ was not significantly different between the treatments (Table 2.5). For the Elba II site, data are not shown because *T. tabaci* populations and damage were very low, and there were no significant differences ($P > 0.05$) between the damage of NP and P treatments, regardless of the cultivars. In Potter, populations of *T. tabaci* were somewhat higher (data not shown) but again there were no significant ($P > 0.05$) differences in the damage between NP and P treatments, except for the cultivar ‘Nebula’ (susceptible check) with damage in the NP treatment of only 10% (data not shown).

Table 2.5. Ratings of onion leaf damage (mean \pm SE) due to *T. tabaci* (Impact on plant growth and yield loss experiments) in Potter, 2007 (7 onion cultivars) at 89 DAT and Elba, 2008 (12 cultivars) at 93 DAT

Cultivar	Potter (2007) ^a		Elba (2008) ^a	
	NP	P	NP	P
NMSU 03-52-1			1.1 \pm 0.3aB	1.0 \pm 0.0aA
Colorado 6	1.9 \pm 0.5aBC	1.0 \pm 0.0bA	1.4 \pm 0.3aB	1.0 \pm 0.0aA
OLYS05N5	1.6 \pm 0.3aC	1.0 \pm 0.0bA	1.4 \pm 0.3aB	1.0 \pm 0.0aA
T-433			1.4 \pm 0.3aB	1.0 \pm 0.0aA
Cometa			1.5 \pm 0.0aB	1.0 \pm 0.0aA
Vaquero			1.5 \pm 0.4aB	1.0 \pm 0.0aA
Delgado	2.8 \pm 0.3aB	1.0 \pm 0.0bA	1.8 \pm 0.3aB	1.0 \pm 0.0bA
Peso	2.0 \pm 0.4aBC	1.0 \pm 0.0bA	1.8 \pm 0.3aB	1.0 \pm 0.0bA
Calibra			1.8 \pm 0.5aB	1.0 \pm 0.0bA
Tioga			1.9 \pm 0.3aB	1.0 \pm 0.0bA
Medeo			2.1 \pm 0.6aB	1.0 \pm 0.0bA
Nebula	4.1 \pm 0.3aA	1.0 \pm 0.0bA	6.6 \pm 0.8aA	2.1 \pm 0.6bA
Yankee	3.8 \pm 0.6aA	1.0 \pm 0.0bA		
Millenium	4.3 \pm 0.7aA	1.0 \pm 0.0bA		
Average	2.9	1.0	2.0	1.1

^a Visual rating for *T. tabaci* leaf damage on a scale ranging from 1 to 9. 1 = no damage; 3 = 25% of the leaves white or with blotches; 5 = 50% of leaves white or with blotches; 7 = 75% of leaves white or with blotches; and 9 = complete damage (100% leaves white).

P= treatment protected with insecticide; NP= treatment nonprotected

Means followed by different lowercase letters within a row or different capital letters within a column are significantly different ($P < 0.05$, Tukey's test)

Thrips tabaci Populations. Counts of larvae were done on the same dates as in the screening experiment. In 2007 in the NP treatment, the susceptible check, 'Nebula', had the highest cumulative number of larvae and was significantly different ($F = 95.99$; $df = 6$; $P < 0.001$) from all the other cultivars (Figure 2.3). The cultivar 'OLYSO5N5' had the lowest number of cumulative larvae and was not significantly different from 'Colorado 6' at 105 DAT. The cultivar 'Peso' had an intermediate number of larvae (Figure 2.3). The cumulative number of larvae on the susceptible cultivar 'Yankee' and 'Delgado' was not significantly different (Figure 2.3);

however, the damage found on ‘Yankee’ in the NP treatment was significantly higher (Table 2.5).

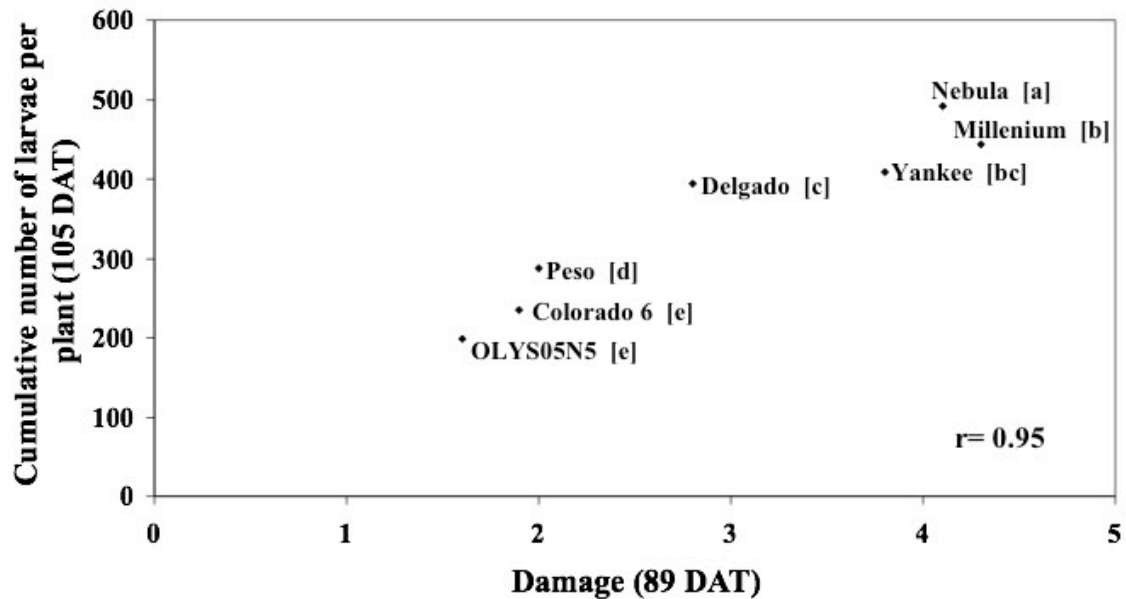


Figure 2.3. Cumulative number of larvae per plant vs damage on seven onion cultivars in the NP treatment (Impact on plant growth experiment, 2007). Cultivars with different letters have significantly different cumulative number of larvae ($P < 0.05$, Tukey’s test).

Figure 2.4 illustrates the cumulative number of *T. tabaci* larvae per plant at 87 DAT and leaf damage at 93 DAT in the NP treatment in 2008. Leaf damage ($F = 52.02$; $df = 11, 3$; $P < 0.001$) and *T. tabaci* populations ($F = 42.60$; $df = 11$; $P < 0.001$) were significantly higher in the susceptible cultivar, ‘Nebula’, compared to the other cultivars. ‘NMSU 03-52-1’ and ‘Colorado 6’ had the lowest populations and damage. ‘Medeo’, even with high *T. tabaci* populations, sustained little damage. The other cultivars, with intermediate *T. tabaci* populations, did not show significant differences in the cumulative number of larvae among them and sustained little damage (Figure 2.4).

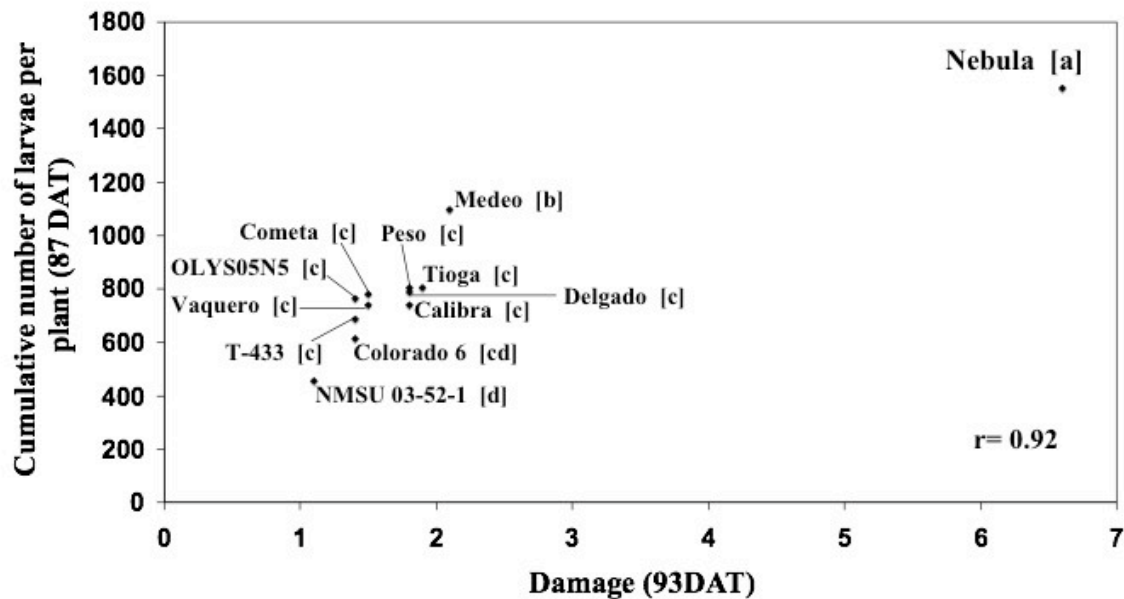


Figure 2.4. Cumulative number of larvae per plant vs damage on 12 onion cultivars in the NP treatment (Yield loss experiment, 2008). Cultivars with different letters have significantly different cumulative number of larvae ($P < 0.05$, Tukey's test).

Plant Height. In 2007, plant height was measured at 91 DAT and for each cultivar there was a significant ($P < 0.05$) decrease in plant height in the nonprotected treatment (Data not shown). The percentage reduction in plant height varied between 15 and 23%, but these differences were not significant ($F = 0.36$; $df = 6, 3$; $P = 0.8949$) (Data not shown).

In 2008, there was a significant decrease in plant height in the NP treatment at 93 DAT in the susceptible check 'Nebula' and in the other cultivars, except for 'Colorado 6', 'T-433' and 'Calibra' (Table 2.6). Percentages of height reduction varied from 2 to 31%. The susceptible check, 'Nebula' had the highest percentage and was significantly ($F = 3.64$; $df = 11, 3$; $P = 0.0019$) different from 'Cometa', 'Delgado', 'Calibra', 'T-433' and 'Colorado 6' (Table 2.6).

Table 2.6. Onion plant height (mean \pm SE) at 93 DAT and bulb weights (mean \pm SE) (Yield loss experiment-Elba, 2008) on 12 onion cultivars

Cultivar	Plant Height (cm) ^a			Bulb Weight (g) ^b		
	P	NP	% Reduction	P	NP	% Reduction
Delgado	64.2 \pm 7.0a	58.3 \pm 7.1b	8.9 \pm 12.0B	54.9 \pm 40.5a	54.4 \pm 31.6a	0.9 \pm 0.6E
Colorado 6	61.7 \pm 7.1a	60.1 \pm 8.0a	2.3 \pm 9.2B	15.7 \pm 11.7a	15.2 \pm 18.0a	3.2 \pm 2.3DE
Peso	66.6 \pm 4.8a	59.5 \pm 6.1b	10.5 \pm 7.0AB	44.5 \pm 31.9a	41.4 \pm 20.0a	7.0 \pm 1.7C-E
T-433	57.0 \pm 4.1a	55.3 \pm 6.7a	3.2 \pm 4.6B	51.2 \pm 27.5a	44.5 \pm 22.7a	13.1 \pm 6.5B-E
Tioga	63.5 \pm 5.5a	53.9 \pm 5.7b	15.0 \pm 6.5AB	45.6 \pm 35.0a	39.5 \pm 22.7a	13.5 \pm 0.7B-E
Calibra	58.2 \pm 7.9a	55.0 \pm 4.7a	4.1 \pm 16.4B	44.9 \pm 29.2a	38.3 \pm 27.5a	14.7 \pm 8.0B-E
Medeo	62.6 \pm 5.9a	48.3 \pm 4.7b	22.7 \pm 6.9AB	51.0 \pm 25.9a	40.9 \pm 30.0a	20.0 \pm 13.8B-E
Vaquero	64.2 \pm 6.8a	58.0 \pm 6.1b	9.4 \pm 8.3AB	63.0 \pm 39.0a	46.5 \pm 32.7a	26.1 \pm 8.4B-D
NMSU 03-52-1	59.2 \pm 6.3a	49.1 \pm 6.1b	17.0 \pm 7.8AB	40.8 \pm 20.9a	30.0 \pm 15.7b	26.5 \pm 11.7BC
Cometa	64.6 \pm 6.5a	58.6 \pm 4.4b	9.1 \pm 6.1B	24.8 \pm 14.2a	18.0 \pm 9.4b	27.5 \pm 4.3BC
OLYS05N5	72.8 \pm 8.4a	64.5 \pm 6.5b	11.3 \pm 2.6AB	34.6 \pm 12.8a	23.8 \pm 10.8b	31.1 \pm 2.2B
Nebula	57.8 \pm 5.0a	40.0 \pm 6.3b	30.8 \pm 6.1A	74.7 \pm 18.5a	34.4 \pm 20.1b	54.0 \pm 21.3A
Average	62.7	55		45.5	35.6	

^a Average of 5 plants per cultivar in 4 replicates

^b Average of 7 plants per cultivar in 4 replicates

P= treatment protected with insecticide; NP= treatment nonprotected

Means followed by different lowercase letters within a row or different capital letters within a column are significantly different (P <0.05, Tukey's test)

Plant Weight. In 2007, at the end of the season, the fresh weight of plants was taken and there were significant ($P < 0.05$) decreases in weight in all the cultivars in the NP treatment, except for ‘Colorado 6’ (Data not shown). Plant weight reductions for cultivars ranged from 17 to 43.5%, but did not differ significantly from each other ($F = 0.75$; $df = 6, 3$; $P = 0.6196$) (Data not shown).

Bulb Weight. Most of the cultivars did not show significant ($P > 0.05$) differences in bulb weight in the NP treatment except for the susceptible cultivar, ‘Nebula’, and the cultivars ‘OLYS05N5’, ‘Cometa’ and ‘NMSU 03-52-1’ (Table 2.6). Bulb weight reductions ranged from 1 to 54%. The susceptible check, ‘Nebula’, had the highest reduction and was significantly ($F = 9.92$; $df = 11, 3$; $P < 0.001$) different from all the other cultivars.

IYSV Infection Assessment. In 2007, a total of 578 onion plants from the experiment on the impact of *T. tabaci* on plant growth were tested for IYSV (Table 2.7). The number of plants tested per cultivar ranged from 37 to 44. Surprisingly, the percentages of IYSV-infected plants in the P and NP treatments were not different, 7.8 and 7.4%, respectively, although plants in the NP treatment had more *T. tabaci*. For ‘Peso’ and ‘Millenium’, the percentage of plants infected with IYSV was even higher in the P treatment compared to the NP treatment (Table 2.7). There were no significant ($P > 0.05$) differences in infection levels between P and NP treatments for any of the cultivars.

In 2008, a total of 672 (28 plants per cultivar) and 642 (22 and 28 plants per cultivar except for ‘NMSU 03-52-1’ which had 16 plants in the P treatment) onion plants were tested in Potter and Elba, respectively (Table 2.7). Surprisingly, the level of infection found was higher for plants in the P treatment in almost every cultivar. In

Potter, the percentages of infected plants in the NP and P treatments were 31.0 and 45.8%, respectively. There were significant ($P < 0.05$) differences between P and NP treatments in the cultivars ‘Nebula’ ($\chi^2 = 4.90$; $df = 1$; $P = 0.0269$), ‘OLYS05N5’ ($\chi^2 = 6.68$; $df = 1$; $P = 0.0098$), ‘Tioga’ ($\chi^2 = 7.36$; $df = 1$; $P = 0.0067$) and ‘Cometa’ ($\chi^2 = 5.26$; $df = 1$; $P = 0.0218$). In Elba, percentages in the NP and P treatments were 37.1 and 58.6%, respectively. There were significant ($P < 0.05$) differences between P and NP treatments in the cultivars ‘OLYS05N5’ ($\chi^2 = 6.17$; $df = 1$; $P = 0.0130$), ‘Colorado 6’ ($\chi^2 = 8.74$; $df = 1$; $P = 0.0031$) and ‘Tioga’ ($\chi^2 = 12.66$; $df = 1$; $P = 0.0004$).

Table 2.7. IYSV incidence on onion plants, as shown by DAS-ELISA, in the impact on plant growth in Potter, 2007 (7 onion cultivars) and in the yield losses experiments in Potter, 2008 (12 cultivars) and Elba, 2008 (12 cultivars)

Cultivar	Trt	Potter 2007 % plants infected (mean \pm SE)	Potter 2008 % plants infected (mean \pm SE)	Elba 2008 % plants infected (mean \pm SE)
Medeo	NP		53.6 \pm 7.1	37.0 \pm 19.1
	P		46.4 \pm 29.4	53.6 \pm 21.4
Peso	NP	6.8 \pm 4.6	21.4 \pm 27.3	35.7 \pm 18.4
	P	12.2 \pm 14.6	39.3 \pm 13.6	50.0 \pm 14.3
Delgado	NP	2.4 \pm 4.8	60.7 \pm 18.0	46.4 \pm 13.7
	P	2.2 \pm 4.4	53.6 \pm 24.4	60.7 \pm 27.0
OLYS05N5	NP	9.5 \pm 11.0	14.3 \pm 11.7*	32.1 \pm 29.5*
	P	10.3 \pm 14.5	46.4 \pm 24.4	64.3 \pm 14.3
Colorado 6	NP	12.5 \pm 5.0	25.0 \pm 24.4	39.3 \pm 13.7*
	P	9.3 \pm 13.2	39.3 \pm 21.4	78.6 \pm 24.7
Tioga	NP		21.5 \pm 18.5*	28.6 \pm 0.0*
	P		57.2 \pm 26.1	78.6 \pm 27.4
Cometa	NP		7.2 \pm 8.3*	17.9 \pm 18.0
	P		32.2 \pm 31.7	35.7 \pm 8.2
Calibra	NP		57.2 \pm 20.2	55.6 \pm 18.6
	P		71.4 \pm 20.2	60.7 \pm 27.0
NMSU 03-52-1	NP		35.7 \pm 24.7	27.3 \pm 23.5
	P		39.3 \pm 18.0	50.0 \pm 0.0
Vaquero	NP		28.6 \pm 11.7	42.9 \pm 20.2
	P		39.3 \pm 29.4	50.0 \pm 31.7
T-433	NP		25.0 \pm 18.0	46.4 \pm 13.7
	P		35.8 \pm 8.3	60.7 \pm 21.4
Nebula	NP	7.5 \pm 9.6	21.5 \pm 18.5*	36.0 \pm 15.3
	P	2.5 \pm 5.0	50.0 \pm 14.3	60.9 \pm 30.1
Yankee	NP	4.6 \pm 5.3		
	P	4.7 \pm 5.4		
Millenium	NP	5.4 \pm 6.2		
	P	13.5 \pm 10.3		
Total plants tested		578	672	642
Avg % infected (NP/P)		7.4/7.8	31.0/45.8	37.1/58.6

* Significantly differences between P and NP treatment per each cultivar ($\alpha = 0.05$, Logistic regression model using PROC GENMOD)

P= treatment protected with insecticide; NP= treatment nonprotected

Discussion

A total of 11 onion cultivars were found to be resistant to *T. tabaci*. In the screening experiment in Potter (2007), eight cultivars ('OLYS05N5', 'Colorado 6', 'Delgado', 'Tioga', 'Peso', 'Cometa', 'Calibra' and 'Medeo') had the lowest damage ratings and there were no significant differences among them. 'Colorado 6', 'OLYS05N5', 'Cometa' and 'Tioga' had the lowest cumulative number of *T. tabaci* larvae. This suggests that these four cultivars may possess antibiosis or antixenosis, or both, as a category of resistance against *T. tabaci*. 'Medeo' and 'Peso' had an intermediate cumulative number of larvae while 'Calibra' and 'Delgado' had cumulative numbers of larvae comparable with the populations observed in the susceptible checks, suggesting that the latter two cultivars may be tolerant to *T. tabaci* populations. In the yield loss experiment in Elba (2008), the same eight cultivars had the lowest *T. tabaci* feeding damage along with 'Vaquero', 'NMSU 03-52-1' and 'T-433' that were included in 2008 experiments. 'NMSU 03-52-1' had the lowest number of *T. tabaci*, indicating strong antibiosis or antixenosis or both, but additional tests will need to be undertaken to determine the resistance category. 'Vaquero' and 'T-433' had intermediate levels of *T. tabaci*, which may indicate a combination of categories of resistance.

The correlation coefficients (r) between *T. tabaci* feeding damage and cumulative number of larvae were not very strong in the screening experiments due to the presence of tolerant cultivars that showed low damage, but supported *T. tabaci* populations similar to the most susceptible cultivars and vice versa where very susceptible cultivars had high damage ratings but low *T. tabaci* populations. However, the regression analyses indicated that *T. tabaci* populations were a significant predictor of leaf damage. Nevertheless, correlation coefficients between *T. tabaci*

feeding damage ratings within the different locations were very strong. This illustrates a consistent response of *T. tabaci* feeding damage across years and locations. Most of the cultivars that showed resistance to *T. tabaci* are considered late maturing. However, late maturity was not the single best indicator of resistance because susceptible cultivars also matured late (Figure 2.2C). This was confirmed by the correlations between days to maturity with *T. tabaci* populations and their feeding damage ratings and by the regression analyses that showed that days to maturity was not a significant ($P > 0.05$) predictor of leaf damage.

Although some cultivars had low populations of *T. tabaci* and showed little feeding damage, there were significant reductions in plant height across all cultivars in the NP treatments in 2007. Also there were significant reductions in fresh plant weight in all the cultivars, except ‘Colorado 6’. This indicates that even low populations that cause low levels of leaf damage could have an impact on growth even on resistant cultivars. These results confirm findings from other field studies, showing the need for lower thresholds than previously proposed (Rueda et al. 2007). In 2008, when populations and damage were somewhat higher, significant reductions in height were observed for nine of the 12 cultivars studied, but significant reductions in bulb weights were observed in only four of the cultivars. This suggests that, at least in some cultivars, height reduction is not necessarily associated with bulb weight reduction.

Percentages of plants infected with IYSV varied from 15 to 79% in the screening experiments in 2008. There was no clear pattern of infection from year to year or from location to location; cultivars that sustained low numbers of *T. tabaci* and showed low leaf damage had high infection rates or vice versa. For example, ‘Vaquero’ had one of the highest infection rates in Potter (50%), but the lowest in Elba (14.8%). Susceptible cultivars to *T. tabaci*, such as ‘Red Zeppelin’, ‘Santana’ and

‘Red Bull’, showed high infection rates in both locations; but other susceptible cultivars such as ‘606-1’ and ‘Yankee’ had low infection rates.

Cultivars that showed resistance to *T. tabaci* also had infection rates that ranged from 15 to 68%. These results suggest that cultivars resistant to *T. tabaci* are not necessarily resistant to the virus and vice versa. This was confirmed by the very low correlations between IYSV percentage of plants infected and damage ratings and between IYSV percentage of plants infected and cumulative number of larvae in the different screening experiments and by the regression analyses that showed that *T. tabaci* populations were not a significant predictor of IYSV infection. Also IYSV percentage of plants infected in the different cultivars varied with field location, as confirmed by the low correlations between IYSV percentage of plants infected in Potter 2007, 2008 and Elba 2008. Surprisingly, onion plants in the P treatments in both places had the highest rates of IYSV infection in both locations in 2008. Joost and Riley (2005), using the electrical penetration graph technique, showed that *Frankliniella occidentalis* (Pergande) probed longer and more frequently on tomato plants treated with imidacloprid compared with untreated plants; it is possible that *T. tabaci* probed more frequently with longer durations in onions protected with spinetoram. This insecticide acts more slowly and may permit longer probing durations before *T. tabaci* mortality occurs; however, this needs to be further studied. Another possible explanation for this is that *T. tabaci* adults migrated from the adjacent, maturing commercial onion field into the P treatments, where onion plants were larger, healthier looking and greener than those in the NP treatments. Thus, selective movement of *T. tabaci* adults into the P treatments could have resulted in an increased likelihood of IYSV transmission in the P treatments. Hsu et al. (2009) recently reported a positive correlation between high numbers of *T. tabaci* adults sampled in onion fields at the end of the season and high levels of IYSV. The authors

suggested that late in the season viruliferous adults were likely migrating from harvested onion fields into nearby unharvested onion fields, where they transmitted IYSV.

HPR has been successfully deployed for several hundred years to control some insect pests in several important field crops, but its use in vegetables has been limited (Stoner 1992, Smith 2005). This has been attributed to several causes, including the difficulty in developing the high levels of resistance necessary to meet the high cosmetic standards required for vegetable crops, as well as the higher market value of vegetable crops that justifies the use of costly insecticides (Stoner 1992). However, there are examples of commercialized or advanced breeding lines developed for host plant resistance in vegetable crops including the following: tomatoes *Lycopersicon esculentum* Mill, resistance to *Tetranychus telarius* (L.) (Gilbert et al. 1974); cucumber, *Cucumis sativus* L., resistance to *Acalymma* sp. and *Diabrotica* sp. (Peterson et al. 1982); potato, *Solanum tuberosum* L., resistance to *Leptinotarsa decemlineata* (Say) (Plaisted et al. 1992); carrot, *Daucus carota* L., resistance to *Psila rosae* (Fabricius) (Ellis 1999); and cabbage, *Brassica oleracea* L. var. *capitata*, resistance to *Trichoplusia ni* (Hübner), *Pieris rapae* (L.), *Plutella xylostella* (L.) (Dickson et al. 1984) and to *T. tabaci* (Shelton et al. 1983, 1998). While our studies identified useful germplasm for HPR in onions to *T. tabaci*, and suggest a strong link between color and resistance, more detailed behavioral studies are needed, so that breeding for HPR can be advanced more quickly. Some studies have suggested that *T. tabaci* avoids onion leaves with light green color (Jones et al. 1935, Coudriet et al. 1979). In the present study only cultivars that were resistant to *T. tabaci* had a visual yellow-green color and these observations were corroborated with Hunter 'b' values measured on 46 onion cultivars, where the 'b' values on the resistant cultivars were among the 15 highest values, which indicates a stronger yellow color on them

compared to the other cultivars (see Table 1). The regression analyses indicated that leaf color (Hunter 'b' values) was a significant predictor of *T. tabaci* feeding damage. Our findings strengthened the hypothesis that leaf color may be a key factor associated with resistance and/or susceptibility of onion cultivars to *T. tabaci*.

Differentiating between yield losses caused by *T. tabaci* and IYSV in open field studies is difficult. IYSV was detected for the first time in the summer of 2006 in New York and it seems the virus is not yet affecting onion yields. In our studies, symptoms of IYSV were mild to absent and appeared late in the season in a scattered pattern, suggesting that reductions in plant size and bulb weight were due to *T. tabaci* feeding rather than IYSV. The overall average percentage of IYSV-infected plants was 10% and 60% in some of the experiments in 2007 and 2008, respectively. This increase should be of concern to onion growers in New York and other areas of recent infection because IYSV incidence increased almost 50% in just one year. If IYSV infects onion plants early in the growing season, the losses may be devastating. Unfortunately, we were not able to identify germplasm resistant to IYSV. However, identifying varieties that have a strong antixenotic effect to the vector might be promising because this trait should mitigate the likelihood of transmission of IYSV.

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REFERENCES

- Ameny, M. A., and P. W. Wilson. 1997.** Relationship between Hunter color values and β -carotene contents in white-fleshed African sweetpotatoes (*Ipomoea batatas* Lam). J. Sci. Food Agric. 73: 301-306.
- Arrieche, N., R. Paz, A. Montagne, and J. Morales. 2006.** Estudios biológicos de *Thrips tabaci* Lindeman (Thysanoptera: Thripidae) en cebolla, en el estado Lara, Venezuela. Bioagro. 18: 149-156.
- Boodley, J. W., and R. Sheldrake. 1977.** Cornell peat-lite mixes for commercial plant growing. Cornell Univ. Coop. Ext. Div. Info. Bull. 43.
- Brar, K. S., A. S. Sidhu, and M. L. Chadha. 1993.** Screening onion varieties for resistance to *Thrips tabaci* Lind. and *Helicoverpa armigera* (Hubner). J. Insect Sci. 6: 123-124.
- Childers, C. C. 1997.** Feeding and oviposition injuries to plants, pp. 505-537. In T. Lewis (ed.), Thrips as crop pests. CAB International, New York, NY.
- Clark, M.F. and A. N. Adams. 1977.** Characteristics of the microplate method of enzyme-linked immunosorbent assay (ELISA) for the detection of plant viruses. J. Gen. Virol. 34: 475-483.
- Coudriet, D. L., A. N. Kishaba, J. D. McCreight, and G. W. Bohn. 1979.** Varietal resistance in onions to thrips. J. Econ. Entomol. 72: 614-615.
- Dickson, M. H., C. J. Eckenrode, and A. E. Blamble. 1984.** NYIR 9602, NYIR 9605, and NYIR 8329 lepidopterous pest-resistant cabbage breeding lines. Hortscience 19: 311-312.
- du Toit, L. J., and G. Q. Pelter. 2005.** Susceptibility of storage onion cultivars to iris yellow spot in the Columbia Basin of Washington, 2005. Biol. Cultural Tests. 20: V006.

- Ellis, P. R. 1999.** The identification and exploitation of resistance in carrots and wild Umbelliferae to the carrot fly, *Psila rosae* (F.). Integrated Pest Management Reviews. 4: 259-268.
- Fournier, F., G. Boivin, and R. K. Stewart. 1995.** Effect of *Thrips tabaci* (Thysanoptera: Thripidae) on yellow onion yields and economic thresholds for its management. J. Econ. Entomol. 88: 1401-1407.
- Gent, D. H., H. R. Schwartz, and R. Khosla. 2004.** Distribution and incidence of *Iris yellow spot virus* in Colorado and its relation to onion plant population and yield. Plant Dis. 88: 446-452.
- Gent, D. H., L. J. du Toit, S. F. Fichtner, S. K. Mohan, H. R. Pappu, and H. F. Schwartz. 2006.** *Iris yellow spot virus*: an emerging threat to onion bulb and seed production. Plant dis. 90: 1468-1480.
- Gilbert, J. C., J. S. Tanaka, and K. Y. Takeda. 1974.** ‘Kewalo’ tomato. Hortscience 9: 481-482.
- Herron, G. A., T. M. James, and J. H. Mo. 2008.** Australian populations of onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), are resistant to some insecticides used for their control. Aust. J. Entomol. 47: 361-364.
- Hoepting, C. A., H. F. Schwartz, and H. R. Pappu. 2007.** First report of *Iris yellow spot virus* on onion in New York. Plant Dis. 91: 327.
- Hsu, C. L., C. A. Hoepting, M. Fuchs, A. M. Shelton, and B. A. Nault. 2010.** Temporal dynamics of *Iris yellow spot virus* and its vector, *Thrips tabaci* (Thysanoptera: Thripidae), in seeded and transplanted onion fields. Environ. Entomol. 39: 266-277.
- Jones, H. A., S. F. Bailey, and S. L. Emsweller. 1935.** Field studies of *Thrips tabaci* Lind. with special reference to resistance in onions. J. Econ. Entomol. 28: 678-680.

- Joost, P. H. and D. G. Riley. 2005.** Imidacloprid effects on probing and settling behavior of *Frankliniella fusca* and *Frankliniella occidentalis* (Thysanoptera: Thripidae) in tomato. J. Econ. Entomol. 98: 1622-1629.
- Kendall, D. M., and J. L. Capinera. 1987.** Susceptibility of onion growth stages to onion thrips (Thysanoptera: Thripidae) damage and mechanical defoliation. Environ. Entomol. 16: 859-863.
- Kennedy, G. G. 2008.** Integration of insect-resistant genetically modified crops within IPM programs, pp. 1-26. In J. Romeis, A. M. Shelton and G.G. Kennedy (eds.), Integration of insect-resistant genetically modified crops within IPM programs. Springer, the Netherlands.
- Loges, V., M.A. Lemos, L. V. Resende, D. Menezes, J.A. Candeia, and V. F. Santos. 2004.** Resistência de cultivares e híbridos de cebola a tripses. Hortic. Bras. 22: 222-225.
- MacIntyre Allen, J. K., C. D. Scott-Dupree, J. H. Tolman, and C. R. Harris. 2005.** Resistance of *Thrips tabaci* to pyrethroid and organophosphorus insecticides in Ontario, Canada. Pest Manag. Sci. 61: 809-815.
- Martin, N. A., P. J. Workman and R. C. Butler. 2003.** Insecticide resistance in onion thrips (*Thrips tabaci*) (Thysanoptera: Thripidae). New Zeal. J. Crop Hort. 31: 99-106.
- Morishita, M. 2008.** Pyrethroid-resistant onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), infesting persimmon fruit. Appl. Entomol. Zool. 43: 25-31.
- Mound, L. A. 1997.** Biological diversity, pp. 197-215. In T. Lewis (ed.), Thrips as crop pests. CAB International, New York, NY.

- Murai, T. 2000.** Effect of temperature on development and reproduction of the onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), on pollen and honey solution. Appl. Entomol. Zool. 35: 499-504.
- (NASS) National Agricultural Statistics Service. 2009.** Vegetables 2008 summary. NASS,USDA(<http://usda.mannlib.cornell.edu/usda/current/VegeSumm/VegeSumm-01-28-2009.pdf>).
- Panda, N., and G. S. Khush. 1995.** Host plant resistance to insects. CAB International, UK.
- Peterson, C.E., P. H. Williams, M. Palmer, and P. Louward . 1982.** Wisconsin 2757 cucumber. HortScience 17: 268.
- Plaisted, R. L., W. M. Tingey and J. C. Steffens. 1992.** The germplasm release of NYL 235-4, a clone with resistance to the Colorado potato beetle. Am. J. Potato Res. 69: 843-846.
- Rueda, A., F. R. Badenes-Perez and A. M. Shelton. 2007.** Developing economic thresholds for onion thrips in Honduras. Crop Protection, 26: 1099-1107.
- SAS Institute. 2003.** SAS/STAT User's Guide, version 9.1.3. SAS institute, Cary, NC.
- Shelton, A. M., R. F. Becker, and J. T. Andaloro. 1983.** Varietal resistance to onion thrips in processing cabbage. J. Econ. Entomol. 76: 85-86.
- Shelton, A. M., J. P. Nyrop, R. C. North, C. Petzoldt, and R. Foster. 1987.** Development and use of a dynamic sequential sampling program for onion thrips, *Thrips tabaci*, on onions. J. Econ. Entomol. 80: 1051-1056.
- Shelton, A. M., W. T. Wilsey, and M. A. Schmaedick. 1998.** Management of onion thrips on cabbage by using plant resistance and insecticides. J. Econ. Entomol. 91: 329-333.

- Shelton, A. M., B. A. Nault, J. Plate, and J. Z. Zhao. 2003.** Regional and temporal variation in susceptibility to λ -Cyhalothrin in onion thrips, *Thrips tabaci* (Thysanoptera: Thripidae) in onion fields in New York. J. Econ. Entomol. 96: 1843-1848.
- Shelton, A. M., J. Z. Zhao, B. A. Nault, J. Plate, F. R. Musser, and E. Larentzaki. 2006.** Patterns of insecticide resistance in onion thrips (Thysanoptera: Thripidae) in onion fields in New York. J. Econ. Entomol. 99: 1798-1804.
- Smith, C. M. 2005.** Plant resistance to arthropods: molecular and conventional approaches. Springer, the Netherlands.
- Stoner, K. A. 1992.** Bibliography of plant resistance to arthropods in vegetables, 1977-1991. Phytoparasitica. 20: 125-180.
- Waiganjo, M. M., J. M. Mueke, and L. M. Gitonga. 2008.** Susceptible onion growth stages for selective and economic protection from onion thrips infestation, pp. 193-200 . In R. K Prange and S. D. Bishop (eds.), Proceedings, Symposium: sustainability through integrated and organic horticulture. International symposium of the International Society for Horticultural Science (ISHS), 13-19 August 2006, Seoul, Korea. Publication Acta Horticulturae. 767. International Society for Horticultural Science, Leuven, Belgium.

CHAPTER 3

Characterization of Resistance and Evaluation of the Attractiveness of Plant Odors on Different Onion Cultivars to Onion Thrips (Thysanoptera: Thripidae)³

Abstract

Onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), a worldwide pest of onion, *Allium cepa* L., can reduce onion yield by more than 50%, and is a vector of *Iris yellow spot virus* (IYSV) that can cause 100% crop losses. In field studies on onion resistance conducted in 2007 and 2008 using 49 cultivars, 11 showed low leaf damage by *T. tabaci* (Diaz-Montano et al. 2010). In controlled laboratory studies, the 11 cultivars, along with two susceptible checks and four additional cultivars, were evaluated to characterize resistance to *T. tabaci*. Two no-choice tests were performed in which plants were individually grown in Cone-tainers™ and two *T. tabaci* adults were introduced and confined. The number of eggs and larvae was counted on each cultivar after 3 and 10 d, respectively. Antixenosis was assessed in choice tests in which all cultivars were planted together in a circle in a single pot, 100 *T. tabaci* adults were released at the center and the number of adults on each plant was evaluated 24 h later. To further understand a possible antixenotic effect, the behavioral response of walking *T. tabaci* adults to plant odors was studied in a glass Y-tube olfactometer. Results indicate that resistant cultivars showed an intermediate-high antibiotic effect to *T. tabaci* and all of them showed a very strong antixenotic effect in

³ Diaz-Montano, J., J. Fail, B. A. Nault, and A. M. Shelton. Characterization of resistance and evaluation of the attractiveness of plant odors on different onion cultivars to onion thrips (Thysanoptera: Thripidae). J. Econ. Entomol. In Preparation.

the choice test. There were no significant preferences in the response of walking *T. tabaci* adults to plant odors. Overall, these results appear promising in helping to identify categories of resistance to *T. tabaci* in onions that can be used in breeding programs.

Resumen (Spanish)

El trips de la cebolla, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), una plaga mundial de la cebolla, *Allium cepa* L., puede causar perdidas en rendimiento > 50%. Además transmite *Iris yellow spot virus* (IYSV), un virus que puede ocasionar 100% de pérdidas del cultivo. En estudios en campo entre 2007 y 2008, se evaluó la resistencia de 49 genotipos de cebolla, y 11 mostraron menor daño de la hoja por *T. tabaci* (Diaz-Montano et al. 2010). En el presente estudio, los 11 genotipos, además de dos testigos susceptibles y otros cuatro genotipos fueron evaluados para caracterizar resistencia a *T. tabaci*. Dos experimentos de no-selección fueron llevados a cabo, en los cuales las plantas fueron sembradas individualmente en Cone-tainers™ y dos adultos de *T. tabaci* fueron introducidos y confinados. El número de huevos y larvas fue contado en cada genotipo después de 3 y 10 días, respectivamente. Antixenosis fue estimada por medio de experimentos de libre selección, en los cuales los diferentes genotipos fueron sembrados en círculo en un mismo recipiente. 100 adultos de *T. tabaci* fueron liberados en el centro del recipiente y el número de adultos en cada planta fue contado 24 horas después. Para comprender mejor un posible efecto antixenotico, las respuestas de adultos de *T. tabaci* hacia olores de las plantas fueron estudiadas usando un olfactómetro de vidrio en forma de Y. Los resultados indican que los genotipos resistentes mostraron un nivel intermedio-alto de antibiosis a *T. tabaci* y un nivel muy fuerte de antixenosis en el experimento de libre selección. No se

presentaron diferencias significativas en la preferencia de adultos de *T. tabaci* hacia olores de plantas. En general, estos resultados son promisorios y ayudan a identificar las categorías de resistencia de la cebolla a *T. tabaci*, las cuales pueden ser incluidas en programas de mejoramiento de cebolla.

Introduction

Onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), is believed to be a native from the eastern Mediterranean region, the center of origin for its most important host plant, onion (*Allium cepa* L.) (Mound 1997). It is a polyphagous pest with a wide host range of more than 100 plant species in more than 30 families (Ghabn 1948, Morison 1957, Ananthakrishnan 1973). *Thrips tabaci* is a cosmopolitan pest of onions wherever they are grown (Lewis 1997), including New York State where a total of 4,290 ha were planted in 2009 (NASS 2010). The rapid development time of *T. tabaci* from egg to adult in less than 15 d at temperatures between 23 and 30°C (Lall and Singh 1968, Gawaad and El-Shazli 1971, Edelson and Magaro 1988, Arrieche et al. 2006) and its high reproductive capacity frequently lead to population outbreaks of this thrips species, especially in hot, dry weather (Bailey 1934, Rueda et al. 2007). *Thrips tabaci* feeding causes silvery leaf spots that turn into white blotches and silvery patches along the leaves (Bailey 1938), and this reduces the photosynthetic ability of the plant (Parella and Lewis 1997). Its feeding can reduce onion bulb weight (Kendall and Capinera 1987, Rueda et al. 2007) and cause yield losses of 50% (Fournier et al. 1995) and 60% (Waiganjo et al. 2008).

Thrips tabaci is also a vector of *Iris yellow spot virus* (IYSV) (family *Bunyaviridae*, genus *Tospovirus*), which was confirmed in the USA in 1989 in Idaho and Oregon (Hall et al. 1993). IYSV has spread to several important onion producing

states in the USA (Gent et al. 2006), including New York where it was confirmed in the summer of 2006 (Hoepting et al. 2007). This virus can reduce bulb size (Gent et al. 2004) and cause 100% crop loss (Pozzer et al. 1999).

Use of foliar insecticides is the most common tactic to control *T. tabaci* on onion but this strategy has led to the development of populations resistant to pyrethroid and organophosphate insecticides in New York (Shelton et al. 2003, 2006), Canada (MacIntyre Allen et al. 2005), and other regions of the world (Martin et al. 2003, Herron et al. 2008, Morishita 2008). Other management practices are needed and host plant resistance is an important one that should be a foundation of an integrated pest management program (Panda and Khush 1995, Kennedy 2008). Since the 1930s, studies on onion resistance to *T. tabaci* have been conducted and resistance has been associated with bulb color (Verma 1966, Lall and Singh 1968, Brar et al. 1993) and leaf structure and color (Jones et al. 1934, 1935; Coudriet et al. 1979, Pawar et al. 1987, Patil et al. 1988, Loges et al. 2004a, 2004b; Diaz-Montano et al. 2010). Despite these efforts on onion resistance to *T. tabaci*, we are not aware of any studies regarding the mechanisms or categories of resistance. There are three categories that characterize host plant resistance to insects: antibiosis, which adversely affects the biology of the insect; antixenosis or non preference, in which the plant is a poor host for the insect and the insect does not feed, lay eggs or find shelter on it, and; tolerance, or the ability of a plant to withstand or recover from insect feeding (Painter 1951, Smith 2005). In our previous studies (Diaz-Montano et al. 2010), 11 onion cultivars that were considered resistant to *T. tabaci* had very little leaf damage as well as lower populations of *T. tabaci* larva compared to susceptible cultivars.

In order to elucidate the categories of resistance of these and other additional onion cultivars, the present studies were conducted with the objectives of

characterizing resistance of onion cultivars to *T. tabaci* by means of no-choice and choice tests.

Materials and Methods

Insect Culture and Plant Material

Thrips tabaci populations used in these experiments were originally collected from onion fields in Yates Co., NY, in August 2008 and these populations were maintained on onion plants under laboratory conditions at 25 °C and 20-40% RH, with a photoperiod of 14:10 (L:D) h. Onions were grown in pots (10.0 cm in diameter by 10.0 cm in height) with four plants per pot.

In this study a total of 17 onion cultivars (Table 3.1) were used. Our previous field studies had identified 11 cultivars that we defined to be resistant to *T. tabaci* based on statistically lower numbers of larvae and leaf damage ratings than susceptible cultivars (Diaz-Montano et al. 2010). The cultivars ‘Nebula’ and ‘Yankee’ were used as the susceptible checks in all the experiments. The other four cultivars were selected for their resistance to *T. tabaci* in Colorado; this information was obtained by personal communication with onion researchers at Colorado State University. Information on days to maturity and bulb color was obtained from the respective companies or the breeder (Table 3.1). Plants were seeded into 200 cell plug trays with one seed per cell (4.5 cm) filled with Cornell mix soil (Boodley and Sheldrake 1977), and then grown under greenhouse conditions at 20-30°C and 20-40% RH with supplemental lights set for a period of 14:10 (L:D) h.

Table 3.1. List of onion cultivars used in this study

Cultivar	Leaf color ^a	Response to <i>T. tabaci</i>	Days to maturity	Seed company
Yankee ¹	Blue-green	Susceptible ^b	108	Bejo
Nebula ¹	Blue-green	Susceptible ^b	100	Nunhems
OLYS05N5 ¹	Yellow-green	Resistant ^b	120	Crookham
Tioga ¹	Yellow-green	Resistant ^b	118	Seminis
Peso ¹	Yellow-green	Resistant ^b	115	Bejo
Calibra ¹	Yellow-green	Resistant ^b	115	Bejo
Vaquero ¹	Yellow-green	Resistant ^b	118	Nunhems
Cometa ²	Yellow-green	Resistant ^b	120	Nunhems
Medeo ¹	Yellow-green	Resistant ^b	106	Bejo
NMSU 03-52-1 ¹	Yellow-green	Resistant ^b	120	^d
Delgado ¹	Yellow-green	Resistant ^b	116	Bejo
T-433 ¹	Yellow-green	Resistant ^b	117	Takii
Colorado 6 ¹	Yellow-green	Resistant ^b	120	Crookham
Arcero ¹	Yellow-green	Resistant ^c	120	Nunhems
Mesquite ¹	Yellow-green	Resistant ^c	120	D. Palmer
White Wing ²	Yellow-green	Resistant ^c	105	Bejo
Granero ¹	Yellow-green	Resistant ^c	118	Nunhems

^{1,2} Bulb color. 1: yellow, 2: white

^a Leaf color obtained by personal observation

^b According to Diaz-Montano et al. (2010)

^c Onion cultivars confirmed as resistant in this study

^d Onion line developed in the program of C.S. Cramer. Department of Plant and Environmental Science, New Mexico State University, Las Cruces, NM

No-Choice Oviposition Test

No-choice tests were performed with the onion cultivars mentioned above (Table 3.1). After 8 wk in the greenhouse, onion plants (between 10 and 15 cm in length and with four leaves) were transplanted individually into 3.8-cm-diameter by 14.0-cm-deep plastic Cone-tainers™ (Ray Leach Conetainer, Hummert International, Earth City, MO) filled with Cornell mix soil (Boodley and Sheldrake 1977) and 10 plants per cultivar were selected and each plant was infested with two similar-aged *T. tabaci* adults. Then a 3.5-cm-diameter by 18.0-cm-height plastic tube (Petro Packaging Company Inc., Cranford, NJ) was inserted into the soil of each plastic

Cone-tainer™ and the upper side of the tube was covered with an organdy cloth (5 x 5 cm) attached by a rubber band. The Cone-tainers™ were placed in racks arranged in a completely randomized design and the racks were put in a climatic chamber (25-30°C and 40% RH, with supplemental lights set for a period of 14:10 (L:D) h).

In order to have similar-aged adults in all the Cone-tainers™, prior to the experiments several *T. tabaci* adults were placed on the susceptible variety, ‘Nebula’, and allowed to lay eggs. Adults were removed after 48 h. The development time of *T. tabaci* on onion from egg to adult is 13.9 d at 30.8°C (Lall and Singh 1968) and 14.2 d at 23°C (Arrieche et al. 2006). Therefore, thrips in this study were left for 15 d until they developed into adults before placing them inside the Cone-tainers™.

The number of eggs laid by the two adults was counted after 3 d of confinement. After the period of confinement, the onion leaves of each plant were placed inside a beaker (100 ml) filled with water, put in a microwave for 40 s and then the eggs were counted using a stereomicroscope. Placing the leaves in the microwave makes the eggs expand and easier to locate and record.

No-Choice Progeny Test

In this experiment exactly the same set up was used as in the no-choice oviposition test: 10 plants per cultivar were selected and each plant was infested with two similar-aged *T. tabaci* adults. The *T. tabaci* progeny (larvae) in each Cone-tainer™ was counted after 10 d of confinement with the two *T. tabaci* adults and the test was repeated one more time with new plants and adult thrips.

Antixenosis (Choice Tests)

Antixenosis was assessed on the same cultivars (Table 3.1) used in the no-choice tests, but not the cultivar ‘Mesquite’. After 10 wk in the greenhouse, one plant

of each cultivar was transplanted and arranged in a circle in a single pot (20 cm in diameter by 20 cm in height, with a distance of ≈ 3.0 cm between plants). Plants in the pots were randomized and the pots were arranged in a completely randomized design with six replications in a climatic chamber as in the no-choice tests. The test was replicated one more time. A total of 100 *T. tabaci* adults were released on a filter paper (15-cm-diameter) placed at the center of the circle of plants. The number of adults on each plant was counted 24 h later.

Olfactometer Experiments

Orientation to or away from a host is one potential aspect of antixenosis by adults. The behavioral response of *T. tabaci* to 17 different onion cultivars (Table 3.1) was studied using a glass Y-tube olfactometer (5 mm inner diameter, 8 cm in length for the base of the tube, and two 5 cm length arms of the tube with an angle of 45° between them) partially following the methods described by Koschier et al. (2000) and Davidson et al. (2008). The Y-tube was placed inside a box (26 x 18 x 18.5 cm) with its inner walls covered with white paper. The base of the Y-tube was connected to a pump that created suction and resulted in an airflow that was regulated to 10 cm/s (~ 0.12 liter/min) in the base using an airflow meter (Cole-Parmer®, Vernon Hills, IL) connected to the silicone tubing between the base of the Y-tube and the pump. Each end of two arms was connected to a glass jar (473 ml, wide mouth glass jar 7.5 cm in diameter by 12 cm in height with a metal screw cap) by means of two polypropylene bulkhead compression unions (06390-20, Cole-Parmer®, Vernon Hills, IL) drilled into the metal screw cap. The air was first purified by passage through a charcoal filter (8131, Alltech®, Activated Charcoal Trap, Alltech Associates, Inc., Deerfield, IL; 37 cm in length by 5.1 cm in diameter acrylic tube). All connections between the pump, the airflow meter, the Y-tube, the two glass jars and the charcoal filter were made with

rigid silicone tubing (6.4 mm inner diameter, R-06406-72, Cole-Parmer®, Vernon Hills, IL). Prior to using the olfactometer, the Y-tube and the two jars connected with the silicone tubing were placed into a bucket filled with water in order to ensure there was no air leakage through the connections. A smoke test showed that at the Y junction the air of the odor-laden arm did not mix with the air of the clean-air arm. After the set up was complete, the Y-tube was positioned at an incline of 25° in the box and the air was drawn through the Y-tube for 5 min before introducing the first *T. tabaci* adult. Experiments were carried out in a dark room at 20-24°C and 40-45% RH. Illumination was provided by two fluorescent tubes fixed ca 40 cm above the box.

After 10 wk in the greenhouse, onion plants from the 17 cultivars (Table 3.1) were placed individually in the odor-laden jar. Plants were gently removed from the potting medium and the soil from the roots was washed off prior to placing into the jar. Before they were used, *T. tabaci* adults of unknown age were confined individually inside 0.6 ml Eppendorf PCR microcentrifuge tubes (Laboratory Products Sales Inc., Rochester, NY). A single thrips of unknown age that had been starved for 2 h was released inside the Y-tube by placing the microcentrifuge tube at the base of the Y-olfactometer after disconnecting the silicone tubing connecting the base of the Y-tube to the pump. The recording time was started after the silicone tube was reconnected to the Y-tube and stopped when the *T. tabaci* adult reached the far end of one of the arms (clean-air or odor-laden). When a thrips made no choice within 5 min, it was removed and replaced by another thrips adult. There were 40 replications (*T. tabaci* adults) per each of the 17 onion cultivars evaluated for a total of 680 thrips in the entire experiment. Four plants were used per each cultivar. After 10 thrips were tested, the onion plant was replaced with a new one and the Y-olfactometer set up was alternated 180° in order to avoid potential position effects. After each cultivar was evaluated, the entire set up was washed with acetone (10%).

Statistical Analyses

For the No-Choice oviposition and Antixenosis tests, analysis of variance (ANOVA) for *T. tabaci* populations (eggs and adults, respectively) among onion cultivars was conducted by using PROC GLM (SAS Institute 2003). Multiple comparisons were computed by using Tukey's studentized (HSD) range test ($P < 0.05$) (SAS Institute 2003). The No-Choice Progeny (larvae) test data did not meet the assumption of homogeneity of variance; therefore, the Games-Howell test was used for pair-wise comparison of the cultivars (SPSS Inc. 2009). The ratio of the No-Choice Tests (larvae/eggs) was calculated to explore the relationship between these two variables. For example, if two cultivars had equal number of eggs but different number of larvae this would suggest an antibiotic effect. For the Olfactometer experiments, the response of *T. tabaci* adults to plant odor or the control for each onion cultivar was compared by the chi-square test for goodness-of-fit ($\alpha = 0.05$) by using PROC FREQ (SAS Institute 2003).

Results

No-Choice Oviposition Test

This experiment was performed to observe the number of eggs laid by two *T. tabaci* confined adults to plants for 3 d. Differences in number of eggs per plant were > 3-fold between the most ('Nebula', 8.8 eggs per plant) and least ('Calibra', 'Vaquero' and 'Delgado', all with 2.3 eggs per plant) susceptible cultivars. Both susceptible checks ('Yankee' and 'Nebula') had significantly ($F = 9.98$; $df = 16, 9$; $P < 0.001$) higher numbers of *T. tabaci* eggs per plant than all other cultivars, except 'Arcero' and 'White Wing' (Table 3.2).

No-Choice Progeny Test

Two no-choice experiments were performed to observe the number of larvae produced by two *T. tabaci* adults confined for 10 d. Although the tests were run on separate dates, they were conducted using identical procedures and thus the two tests were combined and analyzed as a single set of data to increase the power of the test. There were significant differences ($F = 10.62$; $df = 16, 19$; $P < 0.001$) in numbers of *T. tabaci* larvae per plant among the onion cultivars (Table 3.2). The difference in numbers of larvae produced was ca 3-fold between the most ('Yankee', 23.3 larvae per plant) and least ('Delgado', 8.1 larvae per plant) susceptible cultivars. Both susceptible checks ('Yankee' and 'Nebula') had significantly higher numbers of *T. tabaci* larvae per plant than all the cultivars except for 'T-433'. The number of larvae in the cultivar 'T-433' was not significantly different from any other resistant cultivar with the exception of 'Delgado', which had the lowest number of larva (Table 3.2).

Ratio of the No-Choice Tests (larvae/eggs)

The ratio of the no-choice tests (larvae/eggs) among the cultivars varied from 1.7 ('White Wing') to 5.3 ('Calibra'). The ratios of the susceptible cultivars 'Yankee' and 'Nebula' were 3.4 and 2.5, respectively. Although, the susceptible cultivars had the highest number of larvae and eggs, the highest ratios were observed on 'T-433' and 'Calibra'.

Table 3.2. No-choice progeny test and no-choice oviposition test: number of *T. tabaci* larvae and eggs per plant produced by two confined adults on different onion cultivars, 10 and 3 d after infestation, respectively. Free-choice antixenosis test: number of *T. tabaci* adults per plant found on cultivars after 24 h of releasing 100 adults per replicate

Cultivar	No-Choice Progeny Test Larvae (mean \pm SD) ^a	No-Choice Oviposition Test Eggs (mean \pm SD) ^b	Ratio No- Choice Tests (Larvae/Eggs)	Free-Choice Antixenosis Test Adults (mean \pm SD) ^c
Yankee	23.3 \pm 6.4a ^d	6.9 \pm 2.0ab ^e	3.4	15.6 \pm 3.0a ^e
Nebula	21.7 \pm 7.1a	8.8 \pm 1.6a	2.5	15.9 \pm 2.2a
T-433	16.1 \pm 8.6ab	3.3 \pm 2.5c-e	4.9	5.8 \pm 2.8b
Peso	14.2 \pm 4.9b	3.4 \pm 1.6c-e	4.2	5.5 \pm 1.2b
Tioga	13.3 \pm 5.7bc	3.1 \pm 1.9c-e	4.3	4.9 \pm 1.8b
Calibra	12.2 \pm 4.9bc	2.3 \pm 1.3e	5.3	5.0 \pm 1.6b
Granero	12.2 \pm 7.2bc	3.2 \pm 1.5c-e	3.8	3.8 \pm 2.2b
Mesquite	11.9 \pm 4.5bc	2.9 \pm 1.8de	4.1	
Arcero	11.7 \pm 5.0bc	5.9 \pm 1.8a-c	2.0	4.5 \pm 2.1b
OLYS05N5	11.7 \pm 7.0bc	2.9 \pm 1.8de	4.0	4.8 \pm 1.7b
Vaquero	10.7 \pm 4.5bc	2.3 \pm 1.5e	4.7	4.8 \pm 2.2 b
Cometa	10.7 \pm 6.9bc	3.5 \pm 1.6c-e	3.1	4.5 \pm 1.9b
NMSU 03-52-1	10.4 \pm 4.4bc	2.6 \pm 2.0e	4.0	3.8 \pm 1.5b
Medeo	10.2 \pm 3.8bc	2.7 \pm 1.7de	3.8	5.3 \pm 1.8b
Colorado 6	9.6 \pm 3.7bc	3.2 \pm 2.2c-e	3.0	4.2 \pm 2.2b
White Wing	9.4 \pm 4.9bc	5.6 \pm 2.1b-d	1.7	4.0 \pm 1.9b
Delgado	8.1 \pm 3.7c	2.3 \pm 1.6e	3.5	3.6 \pm 1.4b

^a Average of 20 replicates

^b Average of 10 replicates

^c Average of 12 replicates, 100 adults per replicate

^d Within a column, means followed by different letters are significantly different ($P < 0.05$, Games-Howell test)

^e Within a column, means followed by different letters are significantly different ($P < 0.05$, Tukey's test)

Antixenosis (Choice Tests)

Two choice tests were conducted to assess antixenosis or non-preference of *T. tabaci* adults to the different onion cultivars after 24 h. As in the no-choice progeny test, two tests were run on separate dates but were conducted using identical procedures and therefore the two tests were combined and analyzed as a single set of data to increase the power of the test. The two susceptible checks ('Yankee' and 'Nebula') had significantly ($F = 41.65$; $df = 15, 11$; $P < 0.001$) more *T. tabaci* adults per plant than all the other cultivars (Table 3.2). Differences between the numbers of adults were ca 3-5 fold higher for the two susceptible checks compared to the other cultivars. The number of adults per plant among the resistant cultivars did not differ significantly.

Olfactometer

There were no significant differences ($P < 0.05$) in the response of walking *T. tabaci* adults to plant odors or to the control (Table 3.3). Of the 680 *T. tabaci* adults used in this experiment, 481 (71%) reached the far end of one the arms before 60 s and 611 (90%) before 120 s.

Table 3.3. Attractiveness assessment of different onion cultivars odors to *T. tabaci* adults in Y-tube olfactometer experiments

Cultivar	<i>Thrips tabaci</i> Response (%) ^a		χ^2	<i>P</i>
	Control	Onion		
Nebula	45.0	55.0	0.40	0.5271
Yankee	52.5	47.5	0.10	0.7518
Medeo	52.5	47.5	0.10	0.7518
Peso	52.5	47.5	0.10	0.7518
Delgado	50.0	50.0	0.00	1.0000
OLYS05N5	52.5	47.5	0.10	0.7518
Colorado 6	55.0	45.0	0.40	0.5271
Tioga	57.5	42.5	0.90	0.3428
Cometa	57.5	42.5	0.90	0.3428
Calibra	52.5	47.5	0.10	0.7518
NMSU 03-52-1	45.0	55.0	0.40	0.5271
Vaquero	50.0	50.0	0.00	1.0000
T-433	52.5	47.5	0.10	0.7518
Granero	62.5	37.5	2.50	0.1138
Arcero	37.5	62.5	2.50	0.1138
Mesquite	57.5	42.5	0.90	0.3428
White Wing	57.5	42.5	0.90	0.3428

^a 40 replications (*T. tabaci* adults) per cultivar. df= 1, 39. When a thrips made no choice within 5 min, it was replaced. However, 90% of the thrips reached the far end of one the arms before 2 min

Discussion

Results from the free-choice experiments (Table 3.2) suggest a very strong antixenotic effect present in all the resistant cultivars and this supports our previous from previous research (Diaz-Montano et al. 2010) where *T. tabaci* were more attracted to susceptible cultivars with blue-green leaf color than to resistant cultivars that had yellow-green leaf color. However, to interpret the result of the no-choice oviposition test is not straightforward because sometimes it is not easy to differentiate the effect of antibiosis from antixenosis on reduced fecundity of the thrips adults (Panda and Khush 1995, Smith 2005). The strong antixenosis found in all the resistant

cultivars in the free-choice tests may be caused by a plant trait that could reduce the oviposition of *T. tabaci* even in the no-choice oviposition test. The observed reduced fecundity could be due to an initial indirect feeding antixenotic effect i.e reduced feeding, which is associated with reduced oviposition (Bell and Puterka 2004). However, it could also be the result of the adverse effects on the biology of *T. tabaci* adults through feeding on the resistant cultivars for 3 d.

In the no-choice oviposition test, which lasted for 3 d, there were significantly more eggs laid on cultivars ‘Arcero’ and ‘White Wing’ than on cultivars ‘Calibra’, ‘Delgado’, ‘NMSU 03-52-1’ and ‘Vaquero’; however, there were no significant differences in the number of larvae on these cultivars, in the no-choice progeny test, which lasted for 10 d. This result could be either due to increased number of eggs laid by *T. tabaci* adults on the cultivars ‘Calibra’, ‘Delgado’, ‘NMSU 03-52-1’ and ‘Vaquero’ after the 4th day of the no-choice progeny test, which is very unlikely, or more likely due to higher egg and/or larval mortality on the cultivars ‘Arcero’ and ‘White Wing’. Based on this conclusion it seems that the cultivars ‘Arcero’ and ‘White Wing’ have greater antibiotic resistance than the cultivars ‘Calibra’, ‘Delgado’, ‘NMSU 03-52-1’ and ‘Vaquero’. This is reflected in the ratios (larvae/eggs) of ‘Arcero’ and ‘White Wing’ that are the lowest among all cultivars.

On the other hand, the cultivars ‘T-433’, ‘Peso’ and ‘Delgado’ had statistically equal numbers of eggs laid, and significantly fewer larvae were found on ‘Delgado’ than on the other two cultivars. Therefore, it appears that ‘Delgado’ has greater antibiotic resistance than ‘T-433’ and ‘Peso’. The ratio (larvae/eggs) of the cultivar ‘Delgado’ was the lowest among these three cultivars. The ratio of the cultivar ‘T-433’ was the highest because fewer eggs were observed on it but the number of larvae observed on this cultivar was not different from the number on larvae found on the susceptible cultivars.

Similarly, statistically equal numbers of eggs were laid on the susceptible cultivars ‘Nebula’, ‘Yankee’ and ‘Arcero’, and significantly fewer larvae were found on ‘Arcero’ than on the two susceptible onion cultivars. This suggests an antibiotic effect present in the cultivar ‘Arcero’. The ratio (larvae/eggs) of the cultivar ‘Arcero’ was the lowest among these three cultivars because the number of larvae was lower compared to ‘Nebula’ and ‘Yankee’.

The same phenomenon was observed in the cultivars ‘White Wing’ and ‘Yankee’, suggesting a strong antibiotic effect in ‘White Wing’. The ratio (larvae/eggs) of the cultivar ‘White Wing’ was lower between these two cultivars because the number of larvae was lower compared to ‘Yankee’.

The cultivar ‘T-433’ had significantly fewer eggs laid in the no-choice oviposition test compared to the susceptible controls; however, the number of larvae found on this cultivar was statistically equal to the susceptible ‘Nebula’ and ‘Yankee’ in the no-choice progeny test. This suggests that the observed reduced fecundity of the thrips adults in the no-choice oviposition test was due more to an antixenotic effect rather than to antibiosis. When the ratio was calculated, it was expected that the susceptible cultivars would have the highest ratios; however, this was not always the case since some resistant cultivars like ‘T-433’ had significantly lower number of eggs compared to susceptible cultivars but had the same number of larvae as the susceptible checks. Thus, further experiments are needed to discern the reasons for such differences.

The results of the no-choice tests (Table 3.2) documented significant differences between the numbers of larvae and eggs found in some of the cultivars, suggesting an intermediate-high antibiotic effect to *T. tabaci* among the resistant cultivars. Overall, it is concluded that ‘Delgado’, ‘Arcero’ and ‘White Wing’ possess plant traits that are responsible for both antixenotic and antibiotic resistance. However,

the antixenotic resistance of ‘Arcero’ and ‘White Wing’ seems to be less effective because significantly more eggs were laid on these two cultivars compared to ‘Delgado’.

Other studies using Y-tube devices have shown positive responses of *T. tabaci* (den Belder et al. 2001) and *Frankliniella occidentalis* Pergande (de Kogel et al. 1999, Koschier et al. 2000, Davidson et al. 2008) to different plant volatiles. A study using a straight-tube olfactometer showed responses of *Megalurothrips sjostedti* (Trybom) to flowers of different cowpea, *Vigna unguiculata* (L.) Walp., varieties (Ekesi et al. 1998). However, our study on behavioral responses of walking *T. tabaci* adults in the Y-tube olfactometer suggests that there is not an oriented movement towards the onion plant odors, regardless of their susceptibility to *T. tabaci*. According to this study, plant odor does not appear to be the central factor determining *T. tabaci* resistance in onion plants. Although there was not a significant response of *T. tabaci* to either the control or any of the onion cultivars, in the case of the cultivars ‘Arcero’ and ‘Granero’ thrips showed a high response, almost significant, to either the onion plant or the control, respectively. It is likely that with more replications, attractance towards ‘Arcero’ and avoidance of ‘Granero’ could have been detected.

This work also corroborates our previous research findings from field studies (Diaz-Montano et al. 2010) where resistant cultivars had low numbers of *T. tabaci* and low thrips feeding leaf damage ratings. These results from our laboratory experiments help to identify antibiosis and antixenosis as categories of resistance to *T. tabaci* in onions, but additional work is needed to understand the actual mechanisms causing such differences in oviposition and larval development.

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REFERENCES

- Ananthakrishnan, T. N. 1973.** Thrips: biology and control. Macmillan, India. 120 p.
- Arrieche, N., R. Paz, A. Montagne, and J. Morales. 2006.** Estudios biológicos de *Thrips tabaci* Lindeman (Thysanoptera: Thripidae) en cebolla, en el estado Lara, Venezuela. Bioagro. 18: 149-156.
- Bailey, S. F. 1934.** A winter study of the onion thrips in California. California State Dept. Agr.. Mo. Bull. 23: 149-152.
- Bailey, S. F. 1938.** Thrips of economic importance in California. Univ. California, Coll. Agric., Agric. Exp. Stn. Cir. 346.
- Bell, R. L. and G. L. Puterka. 2004.** Modes of host plant resistance to pear psylla: a review. Acta Hort. (ISHS) 663: 183-188.
- Boodley, J. W., and R. Sheldrake. 1977.** Cornell peat-lite mixes for commercial plant growing. Cornell Univ. Coop. Ext. Div. Info. Bull. 43.
- Brar, K. S., A. S. Sidhu, and M. L. Chadha. 1993.** Screening onion varieties for resistance to *Thrips tabaci* Lind. and *Helicoverpa armigera* (Hubner). J. Insect Sci. 6: 123-124.
- Coudriet, D. L., A. N. Kishaba, J. D. McCreight, and G. W. Bohn. 1979.** Varietal resistance in onions to thrips. J. Econ. Entomol. 72: 614-615.
- Davidson M. M., N. B. Perry, L. Larsen, V. C. Green, R. C. Butler, and D. A. J. Teulon. 2008.** 4-Pyridyl Carbonyl Compounds as Thrips Lures: Effectiveness for Western Flower Thrips in Y-Tube Bioassays. J. Agric. Food Chem. 56: 6554-6561.
- de Kogel, W. J., E. H. Koschier, J. H. Visser. 1999.** Y-tube olfactometer to determine the attractiveness of plant volatiles to western flower thrips. Proc. Exp. Appl. Entomol., N.E.V. Amsterdam.10: 131-135.

- den Belder, E., J. Elderson, and I. Agca. 2001.** Is olfactory orientation of *Thrips tabaci* disrupted by a non- host plant? Proc. Exp. Appl. Entomol., N.E.V. Amsterdam.12: 61-64.
- Diaz-Montano, J., M. Fuchs, B. A. Nault and A. M. Shelton. 2010.** Evaluation of onion cultivars for resistance to onion thrips (Thysanoptera: Thripidae) and Iris Yellow Spot Virus. J. Econ. Entomol. 103: 925-937.
- Edelson, J. V., and J. J. Magaro. 1988.** Development of onion thrips, *Thrips tabaci* Lindeman, as a function of temperature. Southwest. Entomol. 13: 171-176.
- Ekesi, S., N. K. Maniania, and I. Onu. 1998.**Antibiosis and antixenosis of two cowpea varieties to the legume flower thrips. Afr. Crop Sci. J. 6: 49-59.
- Fournier, F., G. Boivin, and R.K. Stewart. 1995.** Effect of *Thrips tabaci* (Thysanoptera: Thripidae) on yellow onion yields and economic thresholds for its management, J. Econ. Entomol. 88: 1401-1407.
- Gawaad, A. A. A., and A. Y. El-Shazli. 1971.** Studies on *Thrips tabaci* Lindman. VII. Effect of food on the life cycle. Z. Angew. Entomol. 67: 27-30.
- Gent, D. H., H. R. Schwartz, and R. Khosla. 2004.** Distribution and incidence of *Iris yellow spot virus* in Colorado and its relation to onion plant population and yield. Plant Dis. 88: 446-452.
- Gent, D. H., L. J. du Toit, S. F. Fichtner, S. K. Mohan, H. R. Pappu, and H. F. Schwartz. 2006.** *Iris yellow spot virus*: an emerging threat to onion bulb and seed production. Plant dis. 90: 1468-1480.
- Ghabn, A. A. A. E. 1948.** Contribution to the knowledge of the biology of *Thrips tabaci* Lind. in Egypt. Bull. Soc. Fouad. I Ent. 32: 123-174.
- Hall, J. M., Mohan, K., Knott, E. A. and Moyer, J. W. 1993.** Tospoviruses associated with scape blight of onion (*Allium cepa*) seed crops in Idaho. Plant Dis. 77: 952.

- Herron, G. A., T. M. James, and J. H. Mo. 2008.** Australian populations of onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), are resistant to some insecticides used for their control. Aust. J. Entomol. 47: 361-364.
- Hoepting, C. A., H. F. Schwartz, and H. R. Pappu. 2007.** First report of *Iris yellow spot virus* on onion in New York. Plant Dis. 91: 327.
- Jones, H. A., S. F. Bailey, and S. L. Emsweller. 1934.** Thrips resistance in the onion. Hilgardia. 8: 215-232.
- Jones, H. A., S. F. Bailey, and S. L. Emsweller. 1935.** Field studies of *Thrips tabaci* Lind. with special reference to resistance in onions. J. Econ. Entomol. 28: 678-680.
- Kendall, D. M., and J. L. Capinera. 1987.** Susceptibility of onion growth stages to onion thrips (Thysanoptera: Thripidae) damage and mechanical defoliation. Environ. Entomol. 16: 859-863.
- Kennedy, G. G. 2008.** Integration of insect-resistant genetically modified crops within IPM programs, pp. 1-26. In J. Romeis, A. M. Shelton and G.G. Kennedy (eds.), Integration of insect-resistant genetically modified crops within IPM programs. Springer, the Netherlands.
- Koschier, E. H., W. J. de Kogel, and J. H. Visser. 2000.** Assessing the attractiveness of volatile plant compounds to western flower thrips *Frankliniella occidentalis*. J. Chem. Ecol. 26: 2643-2655.
- Lall, B. S., and L. M. Singh. 1968.** Biology and control of the onion thrips in India. J. Econ. Entomol. 61: 676-679.
- Lewis, T. 1997.** Pest thrips in perspective, pp. 1-13. In T. Lewis (ed.), Thrips as crop pests. CAB International, New York, NY.

- Loges, V., M.A. Lemos, L. V. Resende, D. Menezes, J.A. Candeia, and V. F. Santos. 2004a.** Correlações entre caracteres agronômicos associados à resistência a tripes em cebola. *Hortic. Bras.* 22: 624-627.
- Loges, V., M.A. Lemos, L. V. Resende, D. Menezes, J.A. Candeia, and V. F. Santos. 2004b.** Resistência de cultivares e híbridos de cebola a tripes. *Hortic. Bras.* 22: 222-225.
- MacIntyre Allen, J. K., C. D. Scott-Dupree, J. H. Tolman, and C. R. Harris. 2005.** Resistance of *Thrips tabaci* to pyrethroid and organophosphorus insecticides in Ontario, Canada. *Pest Manag. Sci.* 61: 809-815.
- Martin, N. A., P. J. Workman and R. C. Butler. 2003.** Insecticide resistance in onion thrips (*Thrips tabaci*) (Thysanoptera: Thripidae). *New Zeal. J. Crop Hort.* 31: 99-106.
- Morishita, M. 2008.** Pyrethroid-resistant onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), infesting persimmon fruit. *Appl. Entomol. Zool.* 43: 25-31.
- Morison, G. D. 1957.** A review of British glasshouse Thysanoptera. *Trans. Roy. Ent. Soc. London.* 109: 467-520.
- Mound, L. A. 1997.** Biological diversity, pp. 197-215. In T. Lewis (ed.), *Thrips as crop pests*. CAB International, New York, NY.
- (NASS) National Agricultural Statistics Service. 2010.** Vegetables 2009 summary. NASS,USDA(<http://usda.mannlib.cornell.edu/usda/current/VegeSumm/VegeSumm-01-27-2010.pdf>).
- Painter, R. H. 1951.** Insect resistance in crop plants. ManMillan Co., New York, NY.
- Parrella, M. P., and T. Lewis. 1997.** Integrated pest management (IPM) in field crops, pp. 595-614. In T. Lewis (ed.), *Thrips as crop pests*. CAB International, New York, NY.

- Panda, N., and G. S. Khush. 1995.** Host plant resistance to insects. CAB International, UK.
- Patil, A. P., R. N. Nawale, D. S. Ajri, and P. R. Moholkar. 1988.** Field screening of onion cultivars for their reaction to thrips. Indian Cocoa, Arecanut & Spices J. 12: 10-11.
- Pawar, D. B., U. N. Mote, P. N. Kale, and D. S. Ajri. 1987.** Identification of resistant sources for thrips in onion. Curr. Res. Report. 3: 115-117.
- Pozzer, L., I. C. Bezerra, R. Kormelink, M. Prins, D. Peters, R. de O. Resende, and A. C. de Ávila. 1999.** Characterization of a tospovirus isolate of iris yellow spot virus associated with a disease in onion fields in Brazil. Plant Dis. 83: 345-350.
- Rueda, A., F.R. Badenes-Perez, and A. M. Shelton. 2007.** Developing economic thresholds for onion thrips in Honduras. 26: 1099-1107. Crop Prot.
- SAS Institute. 2003.** SAS/STAT User's Guide, version 9.1.3. SAS institute, Cary, NC.
- Shelton, A. M., B. A. Nault, J. Plate, and J. Z. Zhao. 2003.** Regional and temporal variation in susceptibility to λ -Cyhalothrin in onion thrips, *Thrips tabaci* (Thysanoptera: Thripidae) in onion fields in New York. J. Econ. Entomol. 96: 1843-1848.
- Shelton, A. M., J. Z. Zhao, B. A. Nault, J. Plate, F. R. Musser, and E. Larentzaki. 2006.** Patterns of insecticide resistance in onion thrips (Thysanoptera: Thripidae) in onion fields in New York. J. Econ. Entomol. 99: 1798-1804.
- Smith, C. M. 2005.** Plant resistance to arthropods: molecular and conventional approaches. Springer, the Netherlands.
- SPSS Inc. 2009.** PASW Statistics, version 18.0. SPSS Inc., Chicago, IL.

Verma, S. K. 1966. Studies on the host preference of the onion thrips, *Thrips tabaci* Lindeman to the varieties of onion. Indian J. Entomol. 28: 396-398.

Waiganjo, M. M., J. M. Mueke, and L. M. Gitonga. 2008. Susceptible onion growth stages for selective and economic protection from onion thrips infestation, pp. 193-200 . *In* R. K Prange and S. D. Bishop (eds.), Proceedings, Symposium: sustainability through integrated and organic horticulture. International symposium of the International Society for Horticultural Science (ISHS), 13-19 August 2006, Seoul, Korea. Publication Acta Horticulturae. 767. International Society for Horticultural Science, Leuven, Belgium.

CHAPTER 4

Detection of *Iris yellow spot virus* in Onion Cultivars Using DAS-ELISA⁴

Abstract

Onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), is a global pest of onion, *Allium cepa* L. *Thrips tabaci* feeds directly on leaves causing reduction of onion yield by more than 50%, and can be even more problematic when it transmits *Iris yellow spot virus* (IYSV) that can cause 100% crop loss. In field studies on onion resistance conducted in 2007 and 2008 using 49 cultivars, 11 showed low leaf damage by *T. tabaci* (Diaz-Montano et al. 2010). In the present study, the 11 cultivars resistant to *T. tabaci*, along with six other cultivars, were evaluated to detect the presence of IYSV transmitted by *T. tabaci*. In a laboratory experiment, four plants per cultivar in a single pot (10 pots/cultivar) were confined with 32 *T. tabaci* second instar larvae collected from an IYSV-infected onion field. In a complementary experiment, clean plants were moved to an onion field where IYSV was present. In both tests (laboratory and field), plants were tested for IYSV by DAS-ELISA after 2 and 3 wk, respectively. Although plants were exposed to *T. tabaci* for a short period of time, all onion cultivars were infected with IYSV. Infection rates of the cultivars varied from 3 to 25% and 37 to 70% in the laboratory and field experiments, respectively. From this study and our previous studies, it is concluded that cultivars resistant to *T. tabaci* are not necessarily free of IYSV. Currently, IYSV management relies on sanitation practices, crop rotation, and *T. tabaci* control with insecticides. Genetically

⁴ Diaz-Montano, J., M. Fuchs, B. A. Nault and A. M. Shelton. Detection of *Iris yellow spot virus* in Onion Cultivars Using DAS-ELISA. Plant Health Progr. In Preparation.

engineering onions for resistance to IYSV may be a promising alternative to control IYSV since no natural source of resistance has been found and this approach has proven to be effective in controlling other virus diseases in other crops.

Resumen (Spanish)

El trips de la cebolla, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), es una plaga mundial de la cebolla, *Allium cepa* L. *Thrips tabaci* se alimenta directamente en las hojas y causa una reducción en el rendimiento de cebolla > 50%, y su impacto puede aun ser mayor cuando transmite *Iris yellow spot virus* (IYSV) que puede causar 100% de pérdidas del cultivo. En estudios en campo entre 2007 y 2008, se evaluó la resistencia de 49 genotipos de cebolla, y 11 mostraron menor daño de la hoja por *T. tabaci* (Diaz-Montano et al. 2010). En el presente estudio, estos 11 genotipos resistentes a *T. tabaci*, además de otros seis genotipos fueron evaluados para detectar la presencia de IYSV transmitido por *T. tabaci*. En un experimento en laboratorio, cuatro plantas por variedad fueron transplantadas en un mismo recipiente (10 recipientes/variedad) confinadas con 32 larvas de segundo instar de *T. tabaci* colectadas de un campo de cebolla infectado con IYSV. En un experimento complementario, plantas libres de IYSV fueron llevadas al campo donde IYSV estaba presente. En ambos experimentos (laboratorio y campo), las plantas fueron examinadas con la prueba de DAS-ELISA para detectar IYSV después de 2 y 3 semanas. Aunque las plantas fueron expuestas a *T. tabaci* por un periodo corto de tiempo, todos los genotipos resultaron infectados con IYSV. La tasa de infección en los genotipos osciló entre 3 a 25% y 37 a 70% en los experimentos en el laboratorio y en el campo, respectivamente. De acuerdo a a este estudio y a estudios previos, se concluye que cultivares resistentes a *T. tabaci* no son necesariamente libres del virus.

Actualmente, el manejo de IYSV depende de practicas sanitarias, rotación de cultivo, y control de *T. tabaci* con insecticidas. Cebollas genéticamente modificadas para ser resistentes a IYSV podrían ser una alternativa viable ya que no se han encontrado fuentes naturales de resistencia y esta tecnología ha demostrado ser efectiva en el control de otros virus en otros cultivos.

Introduction

Onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), is a polyphagous pest with a wide host range of more than 100 plant species in more than 30 families (Ghabn 1948, Morison 1957, Ananthakrishnan 1973). *Thrips tabaci* is a widely distributed pest of onions wherever they are grown (Lewis 1997), including New York State where a total of 4,290 ha were planted in 2009 (NASS 2010). *Thrips tabaci* can develop from egg to adult in less than 15 d at 23-30°C (Lall and Singh 1968, Gawaad and El-Shazli 1971, Edelson and Magaro 1988, Arrieche et al. 2006) and this, along with its high reproductive capacity, often leads to population outbreaks, especially in hot, dry weather (Bailey 1934, Rueda et al. 2007). *Thrips tabaci* feeding causes silvery leaf spots that turn into white blotches and silvery patches along the leaves (Bailey 1938). This reduces the photosynthetic ability of the plant (Parella and Lewis 1997) and results in reduction of onion bulb weight (Kendall and Capinera 1987, Rueda et al. 2007) and yield losses of 50% (Fournier et al. 1995) and 60% (Waiganjo et al. 2008).

The use of foliar insecticides is the most common tactic to control *T. tabaci* in onion but this strategy has led to the development of populations resistant to pyrethroid and organophosphate insecticides in North America (Shelton et al. 2003, 2006; MacIntyre Allen et al. 2005) and other regions of the world (Martin et al. 2003, Herron et al. 2008, Morishita 2008). Other management practices have been

investigated including host plant resistance. Different studies on onion resistance to *T. tabaci* have been conducted and resistance has been associated with bulb color (Verma 1966, Lall and Singh 1968, Brar et al. 1993) and leaf structure and color (Jones et al. 1934, 1935; Coudriet et al. 1979, Pawar et al. 1987, Patil et al. 1988, Hudák and Péntzes 2004, Loges et al. 2004a, 2004b; Diaz-Montano et al. 2010).

In addition to the feeding injury, *T. tabaci* transmits *Iris yellow spot virus* (family *Bunyaviridae*, genus *Tospovirus*, IYSV) and is the only confirmed vector of this pathogen (Pozzer et al. 1999, Kritzman et al. 2001). IYSV was first identified on onion in southern Brazil in 1981 (Pozzer et al. 1994), and was confirmed in the USA in 1989 in the Pacific Northwest (Hall et al. 1993). IYSV has spread subsequently throughout other important onion producing states in the USA and worldwide (Gent et al. 2006). IYSV symptoms on leaves appear as lesions (i.e. straw-colored to white, dry, and sometimes elongate) along the edges (Gent et al. 2006). IYSV infection can reduce bulb size (Gent et al. 2004) and cause 100% crop loss (Pozzer et al. 1999).

There have been attempts to identify onion cultivars resistant to IYSV in field conditions with natural populations of *T. tabaci*. The response of 46 onion cultivars to IYSV infection was investigated by du Toit and Pelter (2005) and all cultivars were found susceptible to the virus with infection rates, as determined by visual symptoms, ranging from 58 to 97%. In 2007 and 2008, we tested 47 onion cultivars for resistance to IYSV and the virus was present, as determined by ELISA, in all cultivars but with highly variable rates of infection: 3 to 31% in 2007 and 15 to 79% in 2008 (Diaz-Montano et al. 2010).

In New York, where the virus was found recently (Hoepting et al. 2007), symptoms of IYSV were mild to absent and appeared late in the season (Diaz-Montano et al. 2010, Hsu et al. 2010). Experiments conducted by Diaz-Montano et al. (2010) suggested that reductions in plant size and bulb weight were likely due to *T.*

tabaci feeding rather than IYSV. However, if IYSV infects onion plants early in the growing season, onion yield losses may increase (Diaz-Montano et al. 2010). In our field experiments conducted in 2007 and 2008, all onion cultivars evaluated became infected with IYSV regardless of their susceptibility or resistance to *T. tabaci* or the number of *T. tabaci* found feeding on the cultivars (Diaz-Montano et al. 2010). Cultivars resistant to *T. tabaci* showed equal or higher IYSV infection rates than susceptible varieties (Diaz-Montano et al. 2010).

The present study was conducted in the field and laboratory under more controlled conditions in order to detect IYSV in different onion cultivars.

Materials and Methods

Plant Material

A total of 17 onion cultivars were used in this study (Table 3.1), including 11 cultivars identified as resistant to *T. tabaci* based on lower numbers of larvae and leaf damage ratings than susceptible cultivars (Diaz-Montano et al. 2010). The cultivars ‘Nebula’ and ‘Yankee’ were used as the susceptible checks. The other four cultivars were selected for their resistance to *T. tabaci* in Colorado; this information was obtained by personal communication with onion researchers at Colorado State University. Information on days to maturity and bulb color was obtained from the respective companies or the breeder (Table 3.1). Plants were seeded into 200 cell plug trays with one seed per cell (4.5 cm) filled with Cornell mix soil (Boodley and Sheldrake 1977), and then grown under greenhouse conditions at 20-30°C and 20-40% RH with supplemental lights set for a period of 14:10 (L:D).

Detection of *Iris yellow spot virus* in Onions

To detect the presence of IYSV in onions, experiments were performed under laboratory and field conditions. After 8 wk in the greenhouse, four onion plants per cultivar were transplanted individually into plastic pots (15.0 cm in diameter by 15.0 cm in height, with four plants per pot) filled with Cornell mix soil (Boodley and Sheldrake 1977). Plants were returned to the greenhouse for four additional wk and subsequently the experiments were started.

Laboratory Experiment. Onion plants, infested with *T. tabaci*, from an onion field in Elba, NY (where IYSV visual symptoms were evident) were brought to the lab and a total of 32 *T. tabaci* second instar larvae were confined in each plastic pot with the four plants by using a 15-cm-diameter by 30.0-cm-height acrylic tube that was inserted into the soil of each plastic pot and the upper side of the tube was covered with a plastic lid. The tube had two holes (5 cm in diameter) in the middle and one additional hole (3 cm in diameter) on the center of the lid and all holes were covered at the outer side with an organdy cloth attached with hot melt glue stick by using a hot melt glue gun.

The plastic pots were placed in racks arranged in a completely randomized design and the racks were put in a climatic chamber (25-30°C and 40% RH, with supplemental lights set for a period of 14:10 (L:D) h). Two wk after confinement with the 32 *T. tabaci* larvae, onion leaves were tested for IYSV by double antibody sandwich enzyme-linked immunosorbent assays (DAS-ELISA) (Clark and Adams 1977) and commercially available antibodies, as well as positive and negative controls for IYSV (Agdia Inc., Elkhart, IN). There were 10 pots per cultivar for a total of 40 plants per cultivar. ELISA was used to detect the virus since visual symptoms are less

reliable since asymptomatic plants in New York have been found infected with the virus (Diaz-Montano et al. 2010).

Field Experiment. The plastic pots containing the plants were put within the same commercial onion field (Elba, NY) mentioned above. Pots were left completely open so *T. tabaci* could naturally infest the plants. After a 3 wk exposure period, onion leaves were taken to the lab and tested for IYSV by DAS-ELISA as described above and the number of *T. tabaci* larvae was counted in each pot. There were 10 pots per cultivar for a total of 40 plants per cultivar.

Statistical Analyses

A logistic regression model for IYSV infection rates was performed by using PROC GENMOD and controlled for blocks (SAS Institute 2003). The correlation between laboratory and field IYSV infection rates and the correlation between *T. tabaci* larvae and IYSV rates in the field were compared by using PROC CORR to do the Spearman rank coefficient correlation (SAS Institute 2003).

Results

Detection of *Iris yellow spot virus* in Onions

Laboratory. A total of 472 plants were collected at the end of the experiment; there were between 24 and 40 plants tested per cultivar, except for ‘Medeo’, ‘Calibra’, ‘Mesquite’ and ‘Yankee’ that had 18, 18, 22 and 23 plants tested, respectively. Across all cultivars, only 9% of the plants tested were infected with IYSV. The percentage of plants infected ranged from 2.9 to 25% (Table 4.1) and there were no significant ($\chi^2 = 17.27$; $df = 16$; $P = 0.3685$) differences in infection levels among the cultivars tested.

Field. In the field, 579 plants in total were tested and most of the cultivars had between 28 and 40 plants tested, except for ‘Medeo’ that had 24 plants tested. Across all cultivars, the average percentage of infected plants was 52%. The percentage of plants infected with IYSV varied from 37 to 70% (Table 4.1) and there were no significant differences ($\chi^2 = 16.83$; $df = 16$; $P = 0.3967$) in infection levels among cultivars. The two susceptible checks ‘Nebula’ and ‘Yankee’ had significantly ($F = 29.73$; $df = 16$; $P < 0.001$) more *T. tabaci* larvae than the other cultivars (Table 4.1). There was a low correlation between IYSV infection rates and the number of larvae ($r = 0.452$).

The correlation between laboratory and field IYSV infection rates was very low ($r = -0.279$).

Table 4.1. IYSV incidence, as shown by DAS-ELISA, in experiments under laboratory and field conditions and number of larvae in the field on 17 onion cultivars

Cultivar	Laboratory, % plants infected (mean \pm SD)	Field, % plants infected (mean \pm SD)	Field, No. larvae (mean \pm SD)
NMSU 03-52-1	25.0 \pm 33.9 ^a	36.7 \pm 36.7 ^a	1.1 \pm 3.4 ^c
Medeo	16.7 \pm 26.9 ^a	37.5 \pm 41.4 ^a	4.1 \pm 5.0 ^{bc}
Peso	3.7 \pm 11.7 ^a	41.4 \pm 21.8 ^a	5.9 \pm 5.8 ^b
Cometa	8.3 \pm 26.3 ^a	45.0 \pm 40.5 ^a	5.8 \pm 6.3 ^b
Granero	12.5 \pm 20.1 ^a	46.4 \pm 33.9 ^a	4.6 \pm 5.3 ^{bc}
White Wing	3.3 \pm 10.5 ^a	48.7 \pm 18.9 ^a	7.5 \pm 3.0 ^b
Calibra	16.7 \pm 26.9 ^a	50.0 \pm 41.9 ^a	7.2 \pm 7.8 ^b
Colorado 6	8.8 \pm 14.2 ^a	50.0 \pm 31.1 ^a	3.8 \pm 5.4 ^{bc}
Mesquite	4.5 \pm 14.4 ^a	53.8 \pm 25.5 ^a	4.7 \pm 4.9 ^{bc}
Arcero	13.3 \pm 23.3 ^a	54.3 \pm 28.4 ^a	7.3 \pm 6.3 ^b
OLYS05N5	2.9 \pm 9.0 ^a	55.3 \pm 31.5 ^a	4.7 \pm 5.4 ^{bc}
Vaquero	4.2 \pm 13.2 ^a	56.4 \pm 23.6 ^a	4.0 \pm 4.1 ^{bc}

Table 4.1 (Continued)

Delgado	4.0 ± 12.6a	56.7 ± 35.3a	6.2 ± 6.9b
Yankee	4.3 ± 13.8a	56.8 ± 37.0a	17.3 ± 6.1a
Nebula	9.7 ± 15.6a	63.2 ± 22.2a	20.6 ± 9.1a
T-433	7.5 ± 12.1a	63.2 ± 30.9a	6.3 ± 5.3b
Tioga	8.8 ± 14.2a	69.7 ± 37.9a	5.6 ± 5.5b
No. plants tested	472	579	
Avg. % infected	8.9	52.3	

^a Within a column, means followed by different letters are significantly different ($\alpha = 0.05$, Logistic regression model using PROC GENMOD)

^b Within a column, means followed by different letters are significantly different ($P < 0.05$, Tukey's test)

Discussion

The correlation between laboratory and field IYSV infection rates was very low ($r = -0.279$) indicating that there was not a strong pattern of IYSV infection using these two different experimental procedures. For example, the cultivar 'NMSU 03-52-1' had the highest infection rate in the lab experiment but the lowest in the field while the cultivar 'Tioga', which had the highest infection rate in the laboratory experiment, had one of the lowest in the field. This corresponds with previous studies where more than 40 onion cultivars were tested for IYSV and it was found that cultivars resistant to *T. tabaci* had high levels of IYSV incidence or vice versa from year to year or location to location (Diaz-Montano et al. 2010). However, differences of IYSV infection rates between our laboratory and field tests may also be due to the fixed number of *T. tabaci* used and confined in each pot in the laboratory compared to the unknown number of thrips in the field where pots were left uncovered. Infection may also have been higher because multiple cohorts of viruliferous thrips may have landed on plants in the field, compared with the single cohort used in the laboratory trial.

In the present study, in laboratory and in field experiments all the cultivars became infected with IYSV. In the field experiment, the thrips-susceptible cultivars, ‘Nebula’ and ‘Yankee’, had 63.2 and 56.8% IYSV infection levels, respectively. However, there were no significant differences in IYSV levels between these thrips-susceptible and thrips-resistant cultivars. This result is explained by the low correlation between IYSV infection levels and the number of larvae in the field and suggests that cultivars resistant to *T. tabaci* are not necessarily free of the virus and vice versa, confirming previous studies in which several onion cultivars were tested for IYSV (du Toit and Pelter 2005, Diaz-Montano et al. 2010).

Diaz-Montano et al. (2010) observed that in onion fields in New York visual symptoms of IYSV were mild to absent and usually symptoms appeared at the end of the season and they suggested that reductions in plant and bulb size were due to *T. tabaci* feeding rather than IYSV. This agrees with studies by Hsu et al. (2010) that revealed a positive correlation between high populations of *T. tabaci* adults in onion fields at the end of the season and high levels of IYSV. They suggested that *T. tabaci* adults migrated from harvested onion fields to unharvested onion fields and transmitted the virus. Diaz-Montano et al. (2010) suggested that if IYSV infects onion crops early in the season, the losses might be devastating because IYSV incidence increased ca 50% in 1 yr. In this study, the onion cultivars were exposed to *T. tabaci* populations only for 2 and 3 wk in the laboratory and in the field, respectively; however, all the cultivars became infected with IYSV with infection levels varying from 3 to 25% and 37 to 70% in the laboratory and in the field, respectively.

Our results and those published in the literature have not indicated any onion cultivar resistant to IYSV and/or onion cultivars free of the virus after exposing them to *T. tabaci*. Without such true resistance, efforts to control IYSV should focus on a combination of control management strategies: sanitation practices such as elimination

of volunteer onions and planting of transplants free of *T. tabaci* and the virus; crop rotation; *T. tabaci* control with insecticides and host plant resistance to *T. tabaci*.

There have been several studies on onion resistance to *T. tabaci* as summarized above; however, the traits responsible for resistance have not been well characterized so they can be incorporated into a breeding program. However, our recent studies have identified some *T. tabaci* resistant cultivars and it appears that such resistance is associated with leaf color (Diaz-Montano et al. 2010). We have demonstrated that these cultivars possess strong antixenosis as a category of resistance to *T. tabaci* (Chapter 3) and that leaf color may play an important role in the resistance (Chapter 5). These findings of cultivars with strong antixenosis to *T. tabaci* could have promise for IYSV management because plant traits may prevent the vector to find and colonize these plants. However, the situation is more complex since none of the cultivars examined showed any tolerance to IYSV (du Toit and Pelter 2005, Diaz-Montano et al. 2010). In this case, genetically engineering onions to be resistant to IYSV may be a promising alternative for IYSV management. This strategy has proven extremely effective in controlling *Papaya ringspot virus* in papaya and several viruses in summer squash (Shelton et al. 2008).

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REFERENCES

- Ananthakrishnan, T. N. 1973.** Thrips: biology and control. Macmillan, India. 120 p.
- Arrieche, N., R. Paz, A. Montagne, and J. Morales. 2006.** Estudios biológicos de *Thrips tabaci* Lindeman (Thysanoptera: Thripidae) en cebolla, en el estado Lara, Venezuela. Bioagro. 18: 149-156.
- Bailey, S. F. 1934.** A winter study of the onion thrips in California. California State Dept. Agr.. Mo. Bull. 23: 149-152.
- Bailey, S. F. 1938.** Thrips of economic importance in California. Univ. California, Coll. Agric., Agric. Exp. Stn. Cir. 346.
- Boodley, J. W., and R. Sheldrake. 1977.** Cornell peat-lite mixes for commercial plant growing. Cornell Univ. Coop. Ext. Div. Info. Bull. 43.
- Brar, K. S., A. S. Sidhu, and M. L. Chadha. 1993.** Screening onion varieties for resistance to *Thrips tabaci* Lind. and *Helicoverpa armigera* (Hubner). J. Insect Sci. 6: 123-124.
- Clark, M.F. and A. N. Adams. 1977.** Characteristics of the microplate method of enzyme-linked immunosorbent assay (ELISA) for the detection of plant viruses. J. Gen. Virol. 34: 475-483.
- Coudriet, D. L., A. N. Kishaba, J. D. McCreight, and G. W. Bohn. 1979.** Varietal resistance in onions to thrips. J. Econ. Entomol. 72: 614-615.
- Diaz-Montano, J., M. Fuchs, B. A. Nault and A. M. Shelton. 2010.** Evaluation of onion cultivars for resistance to onion thrips (Thysanoptera: Thripidae) and Iris Yellow Spot Virus. J. Econ. Entomol. 103: 925-937.
- du Toit, L. J., and G. Q. Pelter. 2005.** Susceptibility of storage onion cultivars to iris yellow spot in the Columbia Basin of Washington, 2004. Biol. Cultural Tests. 20: V006.

- Edelson, J. V., and J. J. Magaro. 1988.** Development of onion thrips, *Thrips tabaci* Lindeman, as a function of temperature. Southwest. Entomol. 13: 171-176.
- Fournier, F., G. Boivin, and R.K. Stewart. 1995.** Effect of *Thrips tabaci* (Thysanoptera: Thripidae) on yellow onion yields and economic thresholds for its management, J. Econ. Entomol. 88: 1401-1407.
- Gawaad, A. A. A., and A. Y. El-Shazli. 1971.** Studies on *Thrips tabaci* Lindman. VII. Effect of food on the life cycle. Z. Angew. Entomol. 67: 27-30.
- Gent, D. H., H. R. Schwartz, and R. Khosla. 2004.** Distribution and incidence of *Iris yellow spot virus* in Colorado and its relation to onion plant population and yield. Plant Dis. 88: 446-452.
- Gent, D. H., L. J. du Toit, S. F. Fichtner, S. K. Mohan, H. R. Pappu, and H. F. Schwartz. 2006.** *Iris yellow spot virus*: an emerging threat to onion bulb and seed production. Plant dis. 90: 1468-1480.
- Ghabn, A. A. A. E. 1948.** Contribution to the knowledge of the biology of *Thrips tabaci* Lind. in Egypt. Bull. Soc. Fouad. I Ent. 32: 123-174.
- Hall, J. M., Mohan, K., Knott, E. A. and Moyer, J. W. 1993.** Tospoviruses associated with scape blight of onion (*Allium cepa*) seed crops in Idaho. Plant Dis. 77: 952.
- Herron, G. A., T. M. James, and J. H. Mo. 2008.** Australian populations of onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), are resistant to some insecticides used for their control. Aust. J. Entomol. 47: 361-364.
- Hoepting, C. A., H. F. Schwartz, and H. R. Pappu. 2007.** First report of *Iris yellow spot virus* on onion in New York. Plant Dis. 91: 327.
- Hsu, C. L., C. A. Hoepting, M. Fuchs, A. M. Shelton, and B. A. Nault. 2010.** Temporal dynamics of *Iris yellow spot virus* and its vector, *Thrips tabaci*

- (Thysanoptera: Thripidae), in seeded and transplanted onion fields. Environ. Entomol. 39: 266-277.
- Hudák, K., and B. Péntzes. 2004.** Factors influencing the population of the onion thrips on onion. Acta Phytopathol. Entomol. Hung. 39: 193-197.
- Jones, H. A., S. F. Bailey, and S. L. Emsweller. 1934.** Thrips resistance in the onion. Hilgardia. 8: 215-232.
- Jones, H. A., S. F. Bailey, and S. L. Emsweller. 1935.** Field studies of *Thrips tabaci* Lind. with special reference to resistance in onions. J. Econ. Entomol. 28: 678-680.
- Kendall, D. M., and J. L. Capinera. 1987.** Susceptibility of onion growth stages to onion thrips (Thysanoptera: Thripidae) damage and mechanical defoliation. Environ. Entomol. 16: 859-863.
- Kritzman, A., M. Lampel, B. Raccach, and A. Gera. 2001.** Distribution and transmission of *Iris yellow spot virus*. Plant Dis. 85: 838-842.
- Lall, B. S., and L. M. Singh. 1968.** Biology and control of the onion thrips in India. J. Econ. Entomol. 61: 676-679.
- Lewis, T. 1997.** Pest thrips in perspective, pp. 1-13. In T. Lewis (ed.), Thrips as crop pests. CAB International, New York, NY.
- Loges, V., M.A. Lemos, L. V. Resende, D. Menezes, J.A. Candeia, and V. F. Santos. 2004a.** Correlações entre caracteres agronômicos associados à resistência a tripes em cebola. Hortic. Bras. 22: 624-627.
- Loges, V., M.A. Lemos, L. V. Resende, D. Menezes, J.A. Candeia, and V. F. Santos. 2004b.** Resistência de cultivares e híbridos de cebola a tripes. Hortic. Bras. 22: 222-225.

- MacIntyre Allen, J. K., C. D. Scott-Dupree, J. H. Tolman, and C. R. Harris. 2005.** Resistance of *Thrips tabaci* to pyrethroid and organophosphorus insecticides in Ontario, Canada. Pest Manag. Sci. 61: 809-815.
- Martin, N. A., P. J. Workman, and R. C. Butler. 2003.** Insecticide resistance in onion thrips (*Thrips tabaci*) (Thysanoptera: Thripidae). New Zeal. J. Crop Hort. 31: 99-106.
- Morishita, M. 2008.** Pyrethroid-resistant onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), infesting persimmon fruit. Appl. Entomol. Zool. 43: 25-31.
- Morison, G. D. 1957.** A review of British glasshouse Thysanoptera. Trans. Roy. Ent. Soc. London. 109: 467-520.
- (NASS) National Agricultural Statistics Service. 2010.** Vegetables 2009 summary. NASS,USDA(<http://usda.mannlib.cornell.edu/usda/current/VegeSumm/VegeSumm-01-27-2010.pdf>).
- Parrella, M. P., and T. Lewis. 1997.** Integrated pest management (IPM) in field crops, pp. 595-614. In T. Lewis (ed.), Thrips as crop pests. CAB International, New York, NY.
- Patil, A. P., R. N. Nawale, D. S. Ajri, and P. R. Moholkar. 1988.** Field screening of onion cultivars for their reaction to thrips. Indian Cocoa, Arecanut & Spices J. 12: 10-11.
- Pawar, D. B., U. N. Mote, P. N. Kale, and D. S. Ajri. 1987.** Identification of resistant sources for thrips in onion. Curr. Res. Report. 3: 115-117.
- Pozzer, L., T. Nagata, M. I. Lima, E. W. Kitajima, R. de O. Resende, and A. C. de Ávila. 1994.** "Sapeca": An onion disease in the Sub-Médio São Francisco region, Brazil, is caused by a tospovirus with a serologically distinct nucleocapsid protein. Fitopatol. Bras. 19: 321.

- Pozzer, L., I. C. Bezerra, R. Kormelink, M. Prins, D. Peters, R. de O. Resende, and A. C. de Ávila. 1999.** Characterization of a tospovirus isolate of iris yellow spot virus associated with a disease in onion fields in Brazil. *Plant Dis.* 83: 345-350.
- Rueda, A., F.R. Badenes-Perez, and A. M. Shelton. 2007.** Developing economic thresholds for onion thrips in Honduras. 26: 1099-1107. *Crop Prot.*
- SAS Institute. 2003.** SAS/STAT User's Guide, version 9.1.3. SAS institute, Cary, NC.
- Shelton, A. M., B. A. Nault, J. Plate, and J. Z. Zhao. 2003.** Regional and temporal variation in susceptibility to λ -Cyhalothrin in onion thrips, *Thrips tabaci* (Thysanoptera: Thripidae) in onion fields in New York. *J. Econ. Entomol.* 96: 1843-1848.
- Shelton, A. M., J. Z. Zhao, B. A. Nault, J. Plate, F. R. Musser, and E. Larentzaki. 2006.** Patterns of insecticide resistance in onion thrips (Thysanoptera: Thripidae) in onion fields in New York. *J. Econ. Entomol.* 99: 1798-1804.
- Shelton, A. M., M. Fuchs, and F. Shotkowski. 2008.** Transgenic vegetables and fruits for control of insect and insect-vectored pathogens, pp. 249-272. In J. Romeis, A. M. Shelton and G.G. Kennedy (eds.), *Integration of insect-resistant genetically modified crops within IPM programs*. Springer, the Netherlands.
- Verma, S. K. 1966.** Studies on the host preference of the onion thrips, *Thrips tabaci* Lindeman to the varieties of onion. *Indian J. Entomol.* 28: 396-398.
- Waiganjo, M. M., J. M. Mueke, and L. M. Gitonga. 2008.** Susceptible onion growth stages for selective and economic protection from onion thrips infestation, pp. 193-200. *In* R. K Prange and S. D. Bishop (eds.), *Proceedings, Symposium: sustainability through integrated and organic horticulture*. International symposium of the International Society for Horticultural Science

(ISHS), 13-19 August 2006, Seoul, Korea. Publication *Acta Horticulturae*.

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CHAPTER 5

Effect of Onion Leaf Color on Onion Thrips (Thysanoptera: Thripidae) Preference⁵

Abstract

Onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), is a worldwide pest of onion, *Allium cepa* L. *Thrips tabaci* feeds directly on leaves causing reduction of onion yield by more than 50%. In field studies on onion resistance conducted in 2007 and 2008 using 49 cultivars, 11 showed low leaf damage by *T. tabaci* (Diaz-Montano et al. 2010). In the same study it was suggested that onion leaf color might be a key factor associated with resistance and/or susceptibility of onion cultivars to *T. tabaci* because all onion cultivars that were found resistant to *T. tabaci* had a visual yellow-green leaf color while all the susceptible cultivars had blue-green leaf color. In the present study, the reflectance spectrum of leaves of the 11 resistant cultivars, along with six other cultivars, was measured using a spectrometer to determine if color and/or light reflectance were associated with resistance to *T. tabaci*. Two susceptible cultivars had the highest values of leaf reflectance in the first (275-375 nm) and second (310-410 nm) theoretical photopigment-system of *T. tabaci* and these values were significantly different from most resistant cultivars. Since the two susceptible cultivars always had the highest number of thrips compared to other onion cultivars in previous studies, these results suggest a strong response of *T. tabaci* to onion cultivars

⁵ Diaz-Montano, J., J. Fail, M. Deutschlander, B. A. Nault, and A. M. Shelton. Effect of onion leaf color on onion thrips (Thysanoptera: Thripidae) preference. J. Econ. Entomol. In Preparation.

with higher reflectance in the UV range (270-400 nm). If genes that confer leaf color are identified they could be integrated in onion breeding programs to develop plants that would elicit behavioral responses by *T. tabaci* that would result in non-preference for onion cultivars.

Resumen (Spanish)

El trips de la cebolla, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), una plaga mundial de la cebolla, *Allium cepa* L., se alimenta directamente en las hojas y causa una reducción en rendimiento > 50%. En estudios en campo entre 2008 y 2009, se evaluó la resistencia de 49 genotipos de cebolla, y 11 mostraron menor daño de la hoja por *T. tabaci* (Díaz-Montano et al. 2010). En ese estudio fue sugerido que el color de la hoja de la cebolla podría ser un factor clave asociado con la resistencia y/o susceptibilidad de la cebolla a *T. tabaci* debido a que todas las variedades que fueron resistentes a *T. tabaci* tuvieron un color de la hoja verde-amarilloso mientras que las variedades susceptibles tuvieron un color de la hoja verde-azuloso. En el presente estudio, la reflectancia del espectro de las hojas de los 11 genotipos resistentes, y de otros seis genotipos fue medido usando un espectrómetro para determinar si el color y/o luz reflejada estaba asociado con la resistencia a *T. tabaci*. Dos variedades susceptibles mostraron los valores mas altos de luz reflejada en el primer (275-375 nm) y segundo (310-410 nm) sistema teórico del fotopigmento de *T. tabaci* y estos valores fueron significativamente diferentes a valores en la mayoría de genotipos resistentes. Debido a que en estudios previos estos genotipos susceptibles siempre han tenido los números mas altos de trips que otras variedades de cebolla, estos resultados sugieren una atracción fuerte de *T. tabaci* a variedades de cebolla con las mas altas reflectancias en el rango UV (270-400 nm). Si los genes que confieren color son

identificados, estos podrían ser incorporados en programas de mejoramiento de la cebolla para desarrollar plantas que induzcan respuestas en el comportamiento de *T. tabaci* que resulten en no-preferencia por genotipos de cebolla.

Introduction

Onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), is believed to be a native of the eastern Mediterranean (Mound and Walker 1982, Mound 1997). *Thrips tabaci* has a wide host range compared with other thrips species and has been reported on 140 to 355 plant species in more than 40 families (Ghabn 1948, Morison 1957, Ananthakrishnan 1973). However, onion is a favorite host and is one of the few crops attacked by the same species in different parts of the world (Lewis 1973, 1997). It is present in Europe, North America, South America, Africa, Asia and Australia (Mound 1997). Thrips feeding on onion causes silvery leaf spots that turn into white blotches along the leaves followed by the development of silvery patches and curling of leaves (Bailey 1938). *Thrips tabaci* leaf feeding can reduce onion bulb weight (Kendall and Capinera 1987, Fournier et al. 1995, Rueda et al. 2007, Diaz-Montano et al. 2010) and may cause from 43% (Fournier et al. 1995) to 60% yield loss (Waiganjo et al. 2008). In addition to injury by feeding, *T. tabaci* is a vector of *Iris yellow spot virus* (IYSV) (Pozzer et al. 1999, Kritzman et al. 2001). IYSV symptoms on leaves appear as lesions (i.e. straw-colored to white, dry, and sometimes elongate) along the edges (Gent et al. 2006). IYSV infection can reduce bulb size (Gent et al. 2004) and cause 100% crop loss (Pozzer et al. 1999).

The most common method to control *T. tabaci* populations is the use of foliar chemical insecticides, but *T. tabaci* is difficult to control because insects are found mainly in the narrow spaces between the inner leaves (Shelton et al. 1987) where

spray coverage may be deficient. Additionally, some populations of *T. tabaci* have developed resistance to pyrethroid and organophosphate insecticides in several parts of the world (Martin et al. 2003, Shelton et al. 2003, 2006; MacIntyre Allen et al. 2005, Herron et al. 2008, Morishita 2008). It is important to find alternative management strategies, such as host plant resistance, which should be a foundation of an integrated pest management program (Panda and Khush 1995, Kennedy 2008). Studies on onion resistance to *T. tabaci* have been conducted and resistance has been associated with bulb color (Verma 1966, Lall and Singh 1968, Brar et al. 1993), leaf structure (Jones et al. 1934, 1935; Coudriet et al. 1979, Pawar et al. 1987, Patil et al. 1988, Loges et al. 2004a, 2004b; Hudák and Péntzes 2004) and leaf color (Jones et al. 1935, Diaz-Montano et al. 2010). Jones et al. (1935) compared *T. tabaci* populations on 44 onion cultivars and found that the resistant variety ‘White Persian’, which has light green leaves, had significantly lower numbers of *T. tabaci* than all others. Diaz-Montano et al. (2010) screened 49 onion varieties and found 11 resistant to *T. tabaci*. These resistant varieties had yellow-green colored foliage compared to the susceptible ones that had blue-green color foliage. They suggested that such differences in onion leaf color are strongly associated with resistance to *T. tabaci*.

Studies have indicated that other thrips species respond to different light spectra. Matteson et al. (1992) measured electroretinogram responses of the western flower thrips, *Frankliniella occidentalis* (Pergande), to flashes of lights from 365 to 630 nm and observed two peaks of spectral activity, one in the ultraviolet-A (UV-A) range (315-400 nm, sensitivity peak not determined) and one on the visible range around 540 nm. It has been demonstrated that the thrips *Caliothrips phaseoli* Hood responds to solar UV-B (≤ 315 nm) radiation (Mazza et al. 1999, 2002). Mazza et al. (2010) studied behavioral response of *C. phaseoli* to monochromatic radiation (UV-B, UV-A and visible wavelengths) from 250 to 590 nm and thrips seemed to respond to

wavelengths between 290 and 400 nm. These studies suggest that visual cues may be an important aspect in insect-plant interactions for thrips.

We hypothesized that onion leaf color is associated with resistant to *T. tabaci* (Diaz-Montano et al. 2010). In this study we measured the light reflectance of onion leaves of susceptible and resistant cultivars to determine if there is a relationship between this reflectance and onion resistance to *T. tabaci*.

Materials and Methods

Plant Material

Seventeen onion cultivars were used in this study (Table 3.1). In previous field studies we identified 11 cultivars to be resistant to *T. tabaci* based on their lower numbers of larvae and leaf damage ratings than susceptible cultivars (Diaz-Montano et al. 2010). The other six cultivars included ‘Nebula’ and ‘Yankee’, which were used as the susceptible checks in previous experiments, and four cultivars, which were identified as resistant in field trials conducted in Colorado (personal communication with onion researchers at Colorado State University). Information on days to maturity and bulb color was obtained from the respective companies or the breeder (Table 3.1). Plants were seeded into 200 cell plug trays with one seed per cell (4.5 cm) filled with Cornell mix soil (Boodley and Sheldrake 1977), and then grown under greenhouse conditions at 20-30°C and 20-40% RH with supplemental lights set for a period of 14:10 (L:D) h.

Reflectance Spectrometry

After 8 wk in the greenhouse, four onion plants per cultivar were transplanted individually into plastic pots (15.0 cm in diameter by 15.0 cm in height, with four

plants per pot) filled with Cornell mix soil (Boodley and Sheldrake 1977). Plants were kept in the greenhouse and after 4 wk they were moved to an onion field in Elba, NY. There were 10 pots per cultivar for a total of 40 plants per each cultivar. After, 3 wk onion leaves were collected from the field to measure their light reflectance. Four outer undamaged leaves per cultivar were carefully removed and placed inside labeled plastic bags. Leaves were collected in the morning and their light reflectance spectrum was recorded when the leaves were returned to the laboratory within 3 hr. Until the measurements were completed, all leaves were kept in the sealed plastic bags in a plastic cooler.

The reflectance spectrum of the leaves was recorded using an USB2000+UV-VIS (Ocean Optics, Dunedin, FL) spectrometer and a SS-UV-VIS Integrated Sampling System, which is a combination of RF-excited deuterium UV light source and a tungsten halogen (Ocean Optics, Dunedin, FL). The spectrometer and the lamp were connected through a bifurcated fiber optic probe, fitted at the end with a copper cylinder (inner diameter 7 mm) to standardize measuring distance and shield out ambient light. The probe was held perpendicular to the lower and upper surface of the leaves. Readings were taken on every leaf on intact surface areas, where the leaf cuticle was intact and there were a total of 16 readings per onion cultivar. Reflectance was calculated relative to a WS-2 white standard using the program Spectra-Win. Spectral reflectance was recorded from 170 nm to 880 nm and the spectrometer recorded from 2 to 4 readings per nm in this range. Raw spectra were imported into a spreadsheet program, and then smoothed first by calculating the mean of the 2-4 readings for every nm in the recording range and second by calculating the mean of the 4 readings recorded for every leaf. The following variables were computed from the smoothed spectra: (1) Brightness, which constitutes an estimate of the area under the spectral curve or total light reflected by the leaves, was calculated as the average

reflectance (R_{av}), between 270 and 650 nm. (2) The relative amount of UV reflectance or “UV chroma” was calculated as reflectance in the UV range (270-400 nm) divided by total reflectance [$(R_{270-400}/R_{270-650}) \times 100$] and expressed as a percentage. Although the range of vision and the photopigment-systems that *T. tabaci* possess remain unknown, based on electroretinogram recordings on *F. occidentalis* (Matteson et al. 1992) and observed behavioral response of *C. phaseoli* (Mazza et al. 2010), it was hypothesized that *T. tabaci* has four photopigment-systems with different (partly overlapping) ranges of sensitivity. Photopigment systems are pigments that undergo chemical changes in response to different light wavelengths. The average reflectance (brightness) was computed from the recorded reflectance spectra of onion leaves in the range of sensitivity of all four theoretical photopigment-systems of *T. tabaci*. Accordingly, the average reflectance was computed in the range of sensitivity of the (3) first, 275 to 375 nm (R_{avps1}), (4) second, 310 to 410 nm (R_{avps2}), (5) third, 410 to 510 nm (R_{avps3}) and (6) fourth, 460 to 630 nm (R_{avps4}) theoretical photopigment-systems of *T. tabaci*.

Statistical Analyses

Data were analyzed using Predictive Analytics SoftWare (PASW) Statistics (SPSS Inc. 2009). All computed variables met the assumption of normality. In the case of all computed variables the untransformed data did not meet the assumption of homogeneity of variances, therefore the Games-Howell test was used for pair wise comparisons of the cultivars. All data are reported as original means (\pm 95 % confidence limits). Correlation coefficients (r) were calculated by examining the relationship between *T. tabaci* adults in the Free-Choice Antixenosis Experiment (Table 3.2) and the four theoretical photopigment-systems among the cultivars.

Results

The spectrophotometer device measures a reflectance spectrum from 170 to 880 nm but for the purpose of this study only the spectral reflectance in the theoretical visual spectrum of thrips was analyzed, i.e. 270 to 650 nm. The brightness (R_{av}) or the total light reflected by the leaves on the different onion cultivars ranged between 6.7 and 10.7% (Table 5.1). The susceptible cultivar ‘Yankee’ had the highest reflectance (10.7%) and was significantly ($F = 16.08$; $df = 16, 15$; $P < 0.001$) different from all the other cultivars except for ‘Peso’ with a value of 9.9%. The other susceptible cultivar, ‘Nebula’, had a value of 9.2% and was not significantly different from six other cultivars.

The results from the first theoretical photopigment-system of *T. tabaci* (R_{avps1} , from 275 to 375 nm) showed that the susceptible cultivars ‘Nebula’ and ‘Yankee’, with the highest reflectance values, were significantly ($F = 37.15$; $df = 16, 15$; $P < 0.001$) different from all the other onion cultivars, except for ‘Peso’, ‘Tioga’ and ‘Vaquero’ (Table 5.1). A similar outcome was observed in the second theoretical photopigment-system of *T. tabaci* (R_{avps2} , from 310 to 410 nm) where the susceptible cultivars had the highest values of reflectance and were significantly ($F = 27.07$; $df = 16, 15$; $P < 0.001$) different from all the cultivars except for ‘Peso’, ‘Tioga’ and ‘Vaquero’ (Table 5.1). In the third theoretical photopigment-system of *T. tabaci* (R_{avps3} , from 410 to 510 nm) the values of the two susceptible cultivars were significantly ($F = 12.45$; $df = 16, 15$; $P < 0.001$) different from seven out of the other 15 cultivars (Table 5.1). In the fourth theoretical photopigment-system of *T. tabaci* (R_{avps4} , from 460 to 630 nm) the values of the susceptible cultivars were significantly ($F = 13.91$; $df = 16, 15$; $P < 0.001$) different from only six cultivars (Table 5.1).

The correlation coefficients (r) between *T. tabaci* adults in the Free-Choice Antixenosis Experiment (Table 3.2) and the four theoretical photopigment-systems among the cultivars were 0.71, 0.69, 0.55 and 0.35, respectively.

The relative amount of UV reflectance (UV Chroma, $R_{270-400}/R_{270-650}$) was ca 2-fold between the susceptible checks ('Yankee', 29.9% and 'Nebula', 29.2%) and the cultivars with the lowest amount reflected ('Cometa' and 'Arcero', both with 15.9%) (Table 5.1). The amount of UV reflectance in the two susceptible cultivars was significantly ($F = 79.36$; $df = 16, 15$; $P < 0.001$) different from 11 cultivars that had values between 15.9 and 26.6%.

Table 5.2. Reflectance (%) of: Brightness (R_{av} , 270-650 nm), relative amount of UV reflectance or “UV chroma” [(R270-400/R270-650) x 100] and the four theoretical photopigment-systems of T. tabaci [(Ravps1, 275-375 nm), (Ravps2, 310-410 nm), (Ravps3, 410-510 nm) and (Ravps4, 460-630 nm)] on 17 onion cultivars. All data are reported as original means (\pm 95 % confidence limits)

Cultivars	Ravps1	Ravps2	Ravps3	Ravps4	UV Chroma	Rav
Yankee	9.7 \pm 0.8a	8.8 \pm 0.7a	9.1 \pm 0.6a	12.4 \pm 0.8a	29.9 \pm 1.6a	10.7 \pm 0.6a
Nebula	8.0 \pm 0.6ab	7.4 \pm 0.5ab	8.2 \pm 0.4ab	10.8 \pm 0.5a-c	29.2 \pm 1.0a	9.2 \pm 0.5b
Peso	7.7 \pm 1.2a-c	7.4 \pm 1.1a-c	8.8 \pm 0.9a-c	12.2 \pm 1.0ab	25.8 \pm 1.8a-f	9.9 \pm 1.0a-c
Tioga	6.6 \pm 0.6bc	6.5 \pm 0.6b-d	7.3 \pm 0.6b-d	9.4 \pm 0.6d-f	28.2 \pm 0.7ab	8.0 \pm 0.6b-e
Vaquero	6.6 \pm 0.8b-d	6.3 \pm 0.7b-e	7.7 \pm 0.8a-d	10.3 \pm 0.8b-e	26.6 \pm 0.9bc	8.4 \pm 0.8b-d
Medeo	6.3 \pm 0.3c	5.8 \pm 0.3c-e	6.7 \pm 0.4de	9.3 \pm 0.4ef	27.4 \pm 0.7a-c	7.7 \pm 0.4de
White Wing	6.0 \pm 0.5cd	5.9 \pm 0.5c-f	7.3 \pm 0.6b-d	10.8 \pm 0.8a-e	24.5 \pm 0.6de	8.4 \pm 0.6b-d
Granero	5.9 \pm 0.6c-e	5.8 \pm 0.6c-f	7.6 \pm 0.7a-d	11.4 \pm 0.7ab	23.2 \pm 0.8e-g	8.7 \pm 0.6b-d
Mesquite	5.7 \pm 0.5c-e	5.4 \pm 0.5c-f	6.7 \pm 0.4d-f	9.2 \pm 0.4ef	25.9 \pm 0.8cd	7.4 \pm 0.4d-f
Calibra	5.5 \pm 0.4c-e	5.3 \pm 0.4d-f	6.0 \pm 0.4ef	8.2 \pm 0.5f	27.6 \pm 0.5a-c	6.8 \pm 0.4ef
NMSU 03-52-1	5.4 \pm 0.5c-e	5.3 \pm 0.5c-g	7.2 \pm 0.5b-d	10.9 \pm 0.6 a-c	22.4 \pm 0.9fg	8.2 \pm 0.5b-d
T-433	5.1 \pm 0.3de	5.1 \pm 0.3e-g	7.2 \pm 0.3cd	11.0 \pm 0.4ab	21.5 \pm 0.6gh	8.2 \pm 0.3cd
Delgado	4.7 \pm 0.4ef	4.8 \pm 0.4f-h	7.7 \pm 0.5a-d	11.0 \pm 0.6a-c	20.1 \pm 0.8h	8.1 \pm 0.5b-d
Colorado 6	4.7 \pm 0.4ef	4.7 \pm 0.4f-h	6.5 \pm 0.5d-f	10.3 \pm 0.6b-e	21.4 \pm 0.7gh	7.6 \pm 0.5d-f
OLYS05N5	4.0 \pm 0.4fg	4.0 \pm 0.4hi	5.7 \pm 0.4f	9.3 \pm 0.5d-f	20.1 \pm 0.8h	6.8 \pm 0.4ef
Arcero	3.3 \pm 0.6g	4.0 \pm 0.6g-i	7.7 \pm 0.7a-d	11.0 \pm 0.8a-d	15.9 \pm 1.5i	7.7 \pm 0.7d-f
Cometa	3.0 \pm 0.4g	3.4 \pm 0.4i	6.6 \pm 0.4d-f	9.8 \pm 0.4c-e	15.9 \pm 1.5i	6.7 \pm 0.4f

Average of 16 replicates

Within a column, means followed by different letters are significantly different ($P < 0.05$, Games-Howell test)

Discussion

In our previous research (Diaz-Montano et al. 2010) we suggested that onion leaf color might be a key factor associated with resistance and/or susceptibility of onion cultivars to *T. tabaci* because all resistant onion cultivars had a visual yellow-green leaf color while all susceptible cultivars had blue-green leaf color. In this study, two susceptible cultivars ‘Nebula’ and ‘Yankee’, with blue-green leaf color, were included, and they had the highest values of leaf reflectance in the first (275-375 nm) and second (310-410 nm) theoretical photopigment-system of *T. tabaci* and these values were not significantly different from 3 of the 15 resistant cultivars. Since these two susceptible cultivars ‘Nebula’ and ‘Yankee’ always had the highest number of thrips compared to other onion cultivars, in our previous studies (Diaz-Montano et al. 2010) and chapter 3 (Table 3.1), these results suggest a strong response of *T. tabaci* to onion cultivars with higher reflectance in the UV range (270-400 nm). The strong correlation coefficients between *T. tabaci* adults in the Free-Choice Antixenosis Experiment and the first two theoretical photopigment-systems among the cultivars (0.71 and 0.69, respectively) also suggest a strong response of *T. tabaci* to onion cultivars with higher reflectance in the UV range (270-400 nm). Matteson et al. (1992) observed that *F. occidentalis* responded to wavelengths in the UV-A range (315-400 nm) and Mazza et al. (2010) noticed that *C. phaseoli* were sensitive to wavelength between 290-330 nm. Thus, our results suggest that *T. tabaci* responds to similar wavelengths as *C. phaseoli* and *F. occidentalis*.

The three cultivars (‘Peso’, ‘Tioga’ and ‘Vaquero’), with values of the first and second theoretical photopigment-system of *T. tabaci* not significantly different from the susceptible cultivars, had intermediate populations of *T. tabaci* in previous

experiments (Diaz-Montano et al. 2010). This suggests that *T. tabaci* may be partially attracted to them because of their high values in the UV range.

The results of the third (410-510 nm) and fourth (460-630 nm) theoretical photopigment-system of *T. tabaci* showed that the susceptible cultivars had the highest reflectance values; however, these values were not different from eight and nine of the 15 resistant cultivars in the third and fourth theoretical photopigment-system of *T. tabaci*, respectively. This reinforces the idea that *T. tabaci* are more attracted to the UV light (270-400 nm) rather than to light in the human visual spectrum (390-750 nm) but differs from observations of Matteson et al. (1992) in which *F. occidentalis* were sensitive to a wavelength of 540 nm.

The results of the relative amount of UV reflectance or UV Chroma [UV Range (270-400 nm) /Total Reflectance (270-650 nm)] showed the susceptible cultivars ‘Yankee’ and ‘Nebula’ had the highest values, 29.9% and 29.2%, respectively. This means that ca 30% of the total reflectance is in the UV range for these cultivars. These values were not significantly different from four resistant cultivars including ‘Peso’ and ‘Tioga’ which also did not differ in the values of the first two theoretical photopigment-system of *T. tabaci*. This result corresponds with the outcome of the first two theoretical photopigment-systems of *T. tabaci* and strengthens our hypothesis that *T. tabaci* are more responsive to cultivars with blue-green leaf color than to cultivars with yellow-green color. Moreover, the amount of UV reflectance in the two susceptible cultivars was significantly different from 11 of the 15 resistant cultivars.

The cultivars with significantly lower reflectance than the susceptible cultivars in the first two theoretical photopigment-systems had low (‘Colorado 6’, ‘Cometa’, ‘NMSU 03-52-1’ and ‘OLYS05N5’) and intermediate (‘Calibra’, ‘Delgado’, ‘Medeo’ and ‘T-433’) populations of *T. tabaci* (Diaz-Montano et al. 2010). These same

cultivars (except ‘Medeo’ and ‘Calibra’) and ‘Vaquero’ also showed significantly lower values than susceptible cultivars of UV Chroma (relative amount of UV reflectance). This shows that most of the cultivars resistant to *T. tabaci* had low reflectance in the UV range compared to susceptible checks, and suggests that this contributes to a nonpreference of *T. tabaci* for these resistant cultivars.

The results of brightness (R_{av}) or the total light reflected by the leaves on the different onion cultivars showed the susceptible cultivars ‘Nebula’ and ‘Yankee’ had some of the highest reflectance values, 9.2% and 10.7%, respectively, and were significantly different from eight other cultivars with lower brightness. Three (‘Colorado 6’, ‘Cometa’ and ‘OLYS05N5’) of these eight cultivars had the lowest populations of *T. tabaci* on different experiments while ‘Medeo’ had intermediate populations (Diaz-Montano et al. 2010). There are no published population data for the other four cultivars (‘Arcero’, ‘Granero’, ‘Mesquite’ and ‘White Wing’) that are believed to be resistant according to colleagues in Colorado; however, these cultivars also showed low populations of *T. tabaci* in our experiments (Unpublished data).

Our present results suggest a strong relationship between light spectra reflected by onion leaves and onion resistance to *T. tabaci*, but the actual mechanism for resistance remains unclear. Some studies have shown that some herbivores guard themselves from direct solar radiation by staying on lower leaf surfaces (Whal 2008, Ohtsuka and Osakabe 2009). According to this study, it is possible that *T. tabaci* prefer onion cultivars that reflect a higher amount of light; and this characteristic may provide *T. tabaci* with a shelter from heat and may make these onion cultivars a more preferable host of to *T. tabaci*.

This study indicated a strong response of *T. tabaci* to onion cultivars with higher reflectance in the UV range; however, the range of vision and the photopigment-systems of *T. tabaci* are unknown. Therefore, future work should focus

on studies using electroretinogram recordings and/or observing behavioral responses on *T. tabaci* to different frequencies of light spectra to determine the photopigment-systems of *T. tabaci*. Additionally, the genetic basis of color in onions and its influence on the behavior of *T. tabaci* warrant further investigation.

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REFERENCES

- Ananthakrishnan, T. N. 1973.** Thrips: biology and control. Macmillan, India. 120 p.
- Bailey, S. F. 1938.** Thrips of economic importance in California. Univ. California, Coll. Agric., Agric. Exp. Stn. Cir. 346.
- Boodley, J. W., and R. Sheldrake. 1977.** Cornell peat-lite mixes for commercial plant growing. Cornell Univ. Coop. Ext. Div. Info. Bull. 43.
- Brar, K. S., A. S. Sidhu, and M. L. Chadha. 1993.** Screening onion varieties for resistance to *Thrips tabaci* Lind. and *Helicoverpa armigera* (Hubner). J. Insect Sci. 6: 123-124.
- Coudriet, D. L., A. N. Kishaba, J. D. McCreight, and G. W. Bohn. 1979.** Varietal resistance in onions to thrips. J. Econ. Entomol. 72: 614-615.
- Diaz-Montano, J., M. Fuchs, B. A. Nault and A. M. Shelton. 2010.** Evaluation of onion cultivars for resistance to onion thrips (Thysanoptera: Thripidae) and Iris Yellow Spot Virus. J. Econ. Entomol. 103: 925-937.
- Fournier, F., G. Boivin, and R.K. Stewart. 1995.** Effect of *Thrips tabaci* (Thysanoptera: Thripidae) on yellow onion yields and economic thresholds for its management, J. Econ. Entomol. 88: 1401-1407.
- Gent, D. H., H. R. Schwartz, and R. Khosla. 2004.** Distribution and incidence of *Iris yellow spot virus* in Colorado and its relation to onion plant population and yield. Plant Dis. 88: 446-452.
- Gent, D. H., L. J. du Toit, S. F. Fichtner, S. K. Mohan, H. R. Pappu, and H. F. Schwartz. 2006.** *Iris yellow spot virus*: an emerging threat to onion bulb and seed production. Plant dis. 90: 1468-1480.
- Ghabn, A. A. A. E. 1948.** Contribution to the knowledge of the biology of *Thrips tabaci* Lind. in Egypt. Bull. Soc. Fouad. I Ent. 32: 123-174.

- Herron, G. A., T. M. James, and J. H. Mo. 2008.** Australian populations of onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), are resistant to some insecticides used for their control. Aust. J. Entomol. 47: 361-364.
- Hudák, K., and B. Péntzes. 2004.** Factors influencing the population of the onion thrips on onion. Acta Phytopathol. Entomol. Hung. 39: 193-197.
- Jones, H. A., S. F. Bailey, and S. L. Emsweller. 1934.** Thrips resistance in the onion. Hilgardia. 8: 215-232.
- Jones, H. A., S. F. Bailey, and S. L. Emsweller. 1935.** Field studies of *Thrips tabaci* Lind. with special reference to resistance in onions. J. Econ. Entomol. 28: 678-680.
- Kendall, D. M., and J. L. Capinera. 1987.** Susceptibility of onion growth stages to onion thrips (Thysanoptera: Thripidae) damage and mechanical defoliation. Environ. Entomol. 16: 859-863.
- Kennedy, G. G. 2008.** Integration of insect-resistant genetically modified crops within IPM programs, pp. 1-26. In J. Romeis, A. M. Shelton and G.G. Kennedy (eds.), Integration of insect-resistant genetically modified crops within IPM programs. Springer, the Netherlands.
- Kritzman, A., M. Lampel, B. Raccach, and A. Gera. 2001.** Distribution and transmission of *Iris yellow spot virus*. Plant Dis. 85: 838-842.
- Lall, B. S., and L. M. Singh. 1968.** Biology and control of the onion thrips in India. J. Econ. Entomol. 61: 676-679.
- Lewis, T. 1973.** Thrips: their biology, ecology and economic importance. Academic Press, London. 349 p.
- Lewis, T. 1997.** Pest thrips in perspective, pp. 1-13. In T. Lewis (ed.), Thrips as crop pests. CAB International, New York, NY.

- Loges, V., M.A. Lemos, L. V. Resende, D. Menezes, J.A. Candeia, and V. F. Santos. 2004a.** Correlações entre caracteres agronômicos associados à resistência a tripses em cebola. *Hortic. Bras.* 22: 624-627.
- Loges, V., M.A. Lemos, L. V. Resende, D. Menezes, J.A. Candeia, and V. F. Santos. 2004b.** Resistência de cultivares e híbridos de cebola a tripses. *Hortic. Bras.* 22: 222-225.
- MacIntyre Allen, J. K., C. D. Scott-Dupree, J. H. Tolman, and C. R. Harris. 2005.** Resistance of *Thrips tabaci* to pyrethroid and organophosphorus insecticides in Ontario, Canada. *Pest Manag. Sci.* 61: 809-815.
- Martin, N. A., P. J. Workman, and R. C. Butler. 2003.** Insecticide resistance in onion thrips (*Thrips tabaci*) (Thysanoptera: Thripidae). *New Zeal. J. Crop Hort.* 31: 99-106.
- Matteson, N., I. Terry, A. Ascoli-Christensen, and C. Gilbert. 1992.** Spectral efficiency of the western flower thrips, *Frankliniella occidentalis*. *J. Insect Physiol.* 38: 453-459.
- Mazza C. A., J. Zavala, A. L. Scopel, and C. L. Ballaré. 1999.** Perception of solar UVB radiation by phytophagous insects: behavioral responses and ecosystem implications. *Proc. Natl. Acad. Sci.* 96: 980-985.
- Mazza C. A., M. M. Izaguirre, J. Zavala, A. L. Scopel, and C. L. Ballaré. 2002.** Insect perception of ambient ultraviolet-B radiation. *Ecol. Lett.* 5: 722-726.
- Mazza, C. A., M. M. Izaguirre, J. Curiale, and C. L. Ballare. 2010.** A look into the invisible: ultraviolet-B sensitivity in an insect (*Caliothrips phaseoli*) revealed through a behavioural action spectrum. *Proc. R. Soc. B.* 277: 367-373.
- Morishita, M. 2008.** Pyrethroid-resistant onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), infesting persimmon fruit. *Appl. Entomol. Zool.* 43: 25-31.

- Morison, G. D. 1957.** A review of British glasshouse Thysanoptera. Trans. Roy. Ent. Soc. London. 109: 467-520.
- Mound, L. A. 1997.** Biological diversity, pp. 197-215. In T. Lewis (ed.), Thrips as crop pests. CAB International, New York, NY.
- Mound, L.A., and A. K. Walker. 1982.** Terebrantia (Insecta: Thysanoptera). Fauna of New Zeland. No. 1. 113p.
- Ohtsuka, K., and M. Osakabe. 2009.** Deleterious effects of UV-B radiation on herbivorous spider mites: they can avoid it by remaining on lower leaf surfaces. Environ. Entomol. 38: 920-929.
- Panda, N., and G. S. Khush. 1995.** Host plant resistance to insects. CAB International, UK.
- Patil, A. P., R. N. Nawale, D. S. Ajri, and P. R. Moholkar. 1988.** Field screening of onion cultivars for their reaction to thrips. Indian Cocoa, Arecanut & Spices J. 12: 10-11.
- Pawar, D. B., U. N. Mote, P. N. Kale, and D. S. Ajri. 1987.** Identification of resistant sources for thrips in onion. Curr. Res. Report. 3: 115-117.
- Pozzer, L., I. C. Bezerra, R. Kormelink, M. Prins, D. Peters, R. de O. Resende, and A. C. de Ávila. 1999.** Characterization of a tospovirus isolate of iris yellow spot virus associated with a disease in onion fields in Brazil. Plant Dis. 83: 345-350.
- Rueda, A., F.R. Badenes-Perez, and A. M. Shelton. 2007.** Developing economic thresholds for onion thrips in Honduras. 26: 1099-1107. Crop Prot.
- Shelton, A. M., J. P. Nyrop, R. C. North, C. Petzoldt, and R. Foster. 1987.** Development and use of a dynamic sequential sampling program for onion thrips, *Thrips tabaci*, on onions. J. Econ. Entomol. 80: 1051-1056.

- Shelton, A. M., B. A. Nault, J. Plate, and J. Z. Zhao. 2003.** Regional and temporal variation in susceptibility to λ -Cyhalothrin in onion thrips, *Thrips tabaci* (Thysanoptera: Thripidae) in onion fields in New York. J. Econ. Entomol. 96: 1843-1848.
- Shelton, A. M., J. Z. Zhao, B. A. Nault, J. Plate, F. R. Musser, and E. Larentzaki. 2006.** Patterns of insecticide resistance in onion thrips (Thysanoptera: Thripidae) in onion fields in New York. J. Econ. Entomol. 99: 1798-1804.
- SPSS Inc. 2009.** PASW Statistics, version 18.0. SPSS Inc., Chicago, IL.
- Verma, S. K. 1966.** Studies on the host preference of the onion thrips, *Thrips tabaci* Lindeman to the varieties of onion. Indian J. Entomol. 28: 396-398.
- Wahl, M. 2008.** Ecological modulation of environmental stress: interactions between ultraviolet radiation, epibiotic snail embryos, plants and herbivores. J. Anim. Ecol. 77: 549-557.
- Waiganjo, M. M., J. M. Mueke, and L. M. Gitonga. 2008.** Susceptible onion growth stages for selective and economic protection from onion thrips infestation, pp. 193-200. *In* R. K Prange and S. D. Bishop (eds.), Proceedings, Symposium: sustainability through integrated and organic horticulture. International symposium of the International Society for Horticultural Science (ISHS), 13-19 August 2006, Seoul, Korea. Publication Acta Horticulturae. 767. International Society for Horticultural Science, Leuven, Belgium.

Epilogue

In this epilogue, I provide a summary of the main findings of the research, discuss their implications and suggest further research.

Chapter 1 contains a review, which emphasizes important aspects of the history, biology, ecology and current management strategies (chemical, biological and cultural control and host plant resistance) of onion thrips, *Thrips tabaci* (Thysanoptera: Thripidae), in onion, *Allium cepa* L., and suggests future work on this important global pest of onion. *Thrips tabaci* is a cosmopolitan and polyphagous pest on more than 140 plant species within 40 families; however, onions are its favorite host. Several factors contribute to the high pest status of *T. tabaci*, including a rapid development time from egg to adult on onion in < 15 d at temperatures between 23 and 30°C. Its short generation time, coupled with its high reproductive capacity, frequently leads to population outbreaks.

Thrips tabaci is considered an indirect pest of dry bulb onion because it feeds on leaves; however, *T. tabaci* leaf feeding can reduce onion bulb weight resulting in yield losses of 60%. In addition to injury by feeding, *T. tabaci* transmits *Iris yellow spot virus* (family *Bunyaviridae*, genus *Tospovirus*, IYSV). IYSV infection can reduce bulb size and cause 100% crop loss. Thus, besides the losses caused by direct feeding by *T. tabaci*, this virus poses a serious additional threat to onion production.

For several decades, the frequent use of foliar insecticides has been the main tactic to manage *T. tabaci*. However, coverage with foliar applied insecticides is difficult in the narrow spaces between inner leaves where *T. tabaci* are found. Additionally, some populations of *T. tabaci* have developed resistance to pyrethroid and organophosphate insecticides in several parts of the world.

Other management strategies for *T. tabaci* have been attempted, but these strategies have not yet been widely adopted; thus, it seems that foliar insecticides will continue to be widely used against *T. tabaci*. However, host plant resistance in onion has not been widely studied for control of *T. tabaci* and IYSV and may hold promise as a major component for integrated pest management (IPM) of this important crop.

Chapter 2 contains studies assessing the impact of *T. tabaci* and IYSV on plant growth and yield on different onion cultivars in the field over a 2-year period. Forty-nine cultivars were evaluated and 11 had very little leaf damage and were considered resistant to *T. tabaci*. These cultivars had low to intermediate numbers of *T. tabaci* larvae compared to susceptible cultivars, suggesting a possible combination of categories of resistance. Visual assessment indicated that all resistant cultivars had yellow-green colored foliage, whereas the other 38 had blue-green colored foliage. In treatments not protected from *T. tabaci* there were significant reductions in plant height and plant weight in most of the resistant cultivars, but there were reductions in bulb weight only in a few of them. Although there were some differences, all the cultivars evaluated became infected with IYSV. Furthermore, cultivars resistant to *T. tabaci* were not necessarily resistant to the virus and vice versa. The average of plants infected with IYSV was 10% in 2007 and 60% in 2008.

Chapter 3 contains studies on choice and no-choice tests performed to characterize resistance of different onion cultivars to *T. tabaci*. No-choice tests indicated that resistant cultivars showed an intermediate to high antibiotic effect to *T. tabaci*. Free choice experiments showed a very strong antixenotic effect in all the resistant cultivars, which corresponds with results in chapter 2 where all resistant cultivars had yellow-green leaf color and all susceptible cultivars had blue-green leaf color. Another study on behavioral responses of walking *T. tabaci* adults using a Y-

tube olfactometer suggested that there is not an oriented movement towards onion plant odors.

Chapter 4 contains studies conducted under controlled conditions with the objective to detect the presence of IYSV transmitted by *T. tabaci* on the different onion cultivars. In a laboratory experiment, plants were infested with *T. tabaci* second instar larvae from an IYSV-infected commercial onion field and thrips were confined to the plants. In a complementary experiment, greenhouse-raised plants free from IYSV were moved to an infected IYSV-field and plants were allowed to be infested by naturally occurring *T. tabaci*. In both tests, the plants were tested for IYSV by DAS-ELISA test after 2 and 3 wk in the laboratory and in the field, respectively. The cultivars were exposed to *T. tabaci* for a short period of time; however, they all became infected with IYSV. The infection varied from 3 to 25% and 37 to 70% in the laboratory and field experiments, respectively. From previous studies and this study, it is concluded that some cultivars had lower levels of infection by IYSV but that no cultivars were resistant and that those that were resistant to *T. tabaci* were not necessarily free of the virus.

Chapter 5 contains studies measuring the reflectance spectrum of onion leaves of susceptible and resistant onion cultivars using a spectrometer in order to determine if color and/or light reflectance were associated with resistance to *T. tabaci*. In chapters 2 and 3 it was suggested that onion leaf color might be a key factor associated with resistance and/or susceptibility of onion cultivars to *T. tabaci* because all onion cultivars that were found resistant to *T. tabaci* had a visual yellow-green leaf color while all the susceptible cultivars had blue-green leaf color. In this study, susceptible cultivars had the highest values of leaf reflectance in the first (275-375 nm) and second (310-410 nm) theoretical photopigment-system of *T. tabaci* and these values were significantly different from most resistant cultivars. Since the two susceptible

cultivars always had the highest number of thrips compared to other onion cultivars in previous studies, these results indicated a strong response of *T. tabaci* to onion cultivars with higher reflectance in the UV range (270-400).

Implications and Future Work

Host plant resistance (HPR) to insects has been successfully employed to control insect pests in several important field crops; however, its use in vegetable crops has been limited. This is mainly due to the difficulty in developing high levels of resistance that also meet the high aesthetic levels required for vegetable crops. Additionally, the higher market value of vegetable crops still allows the use of costly insecticides. However, some resistant breeding lines have been developed in vegetable crops and this may bode well for management of *T. tabaci* on onions.

HPR may offer a long-term solution to *T. tabaci* and IYSV control. Several studies have been conducted on onion resistance to *T. tabaci* since the 1930s and some of them seem promising; however, the characteristics responsible for resistance have not been well characterized and much more work is needed. The study on resistance to IYSV, a much newer pest, is in its earlier stages of investigation. The work conducted in this dissertation was performed with the purpose of advancing the knowledge of onion resistance to *T. tabaci* and IYSV.

Our findings identified useful onion germplasm resistant to *T. tabaci* and indicated potential for developing onion resistance to this insect pest as a part of an overall IPM strategy. Experiments in this study helped to identify antibiosis and antixenosis as categories of resistance to *T. tabaci* in onions and suggested a strong relationship between onion leaf color and resistance to *T. tabaci*. This work suggested that *T. tabaci* responds to light reflectance in the UV range. The genes that confer this

specific physical characteristic in onion leaves should be investigated as they may hold a key for creating onion plants that would elicit behavioral responses by *T. tabaci* and would result in decreased likelihood of it finding the leaves a suitable habitat. Since it seems that leaf color is associated with resistance in the onion cultivars found in this study, regions of DNA that control this trait can potentially be identified by linking phenotypic data with genotypic data through such tactics as Quantitative Trait Loci (QTL) analysis. QTLs are regions of DNA associated with genes contributing to the phenotypic trait. Candidate genes residing within these regions may be identified and isolated and then transferred to generate onion resistant cultivars using marker-assisted breeding.

Although this research indicated a strong response of *T. tabaci* to onion cultivars with higher reflectance in the UV range, the range of vision and the photopigment-systems that *T. tabaci* possess remain unknown. Thus, future work should focus on conducting studies using electroretinogram recordings and/or observing behavioral responses of *T. tabaci* to different frequencies of light spectra to determine the photopigment-systems that *T. tabaci* possess. In order to perform electroretinogram recordings, an electrode is inserted under the cornea of the insect's eye and a ground electrode is placed on another part of the insect body such as the thorax. Electroretinogram measures electrical responses from a number of photoreceptors that can be very useful in identifying properties of *T. tabaci* vision. Another way to approach the problem is to observe behavioral responses to different wavelengths of light using sticky cards, water pan traps or other traps of different colors.

According to our work, plant odor does not appear to be the central factor determining *T. tabaci* resistance in onion plants, however, there may be merit in continuing these studies. For example, although there was not a significant response of

T. tabaci to either the control or any of the onion cultivars, in the case of two cultivars, *T. tabaci* showed a high response, almost significant, to either the onion plant or the control (clean air), respectively. It is possible that with more replications, a behavioral response to these two cultivars could have been detected. There were 40 replications per cultivar used in this study.

As mentioned before, the resistant cultivars found in this dissertation possess strong antixenosis as a category of resistance to *T. tabaci*. This response may also hold promise for management of IYSV because plant traits prevent the vector from finding and colonizing these plants and may reduce the likelihood of transmission of IYSV. However, because of the ease of transmission of the virus, the avoidance of the plant by the insect would have to be very strong. Without such true resistance to IYSV at present, efforts to control IYSV should focus on a combination of control management strategies such as sanitation practices, planting of transplants free of *T. tabaci* and the virus, crop rotation and *T. tabaci* control with insecticides. In the long run, genetically engineering onions resistant to IYSV may be the only viable solution to manage IYSV since no natural source of resistance has been found and this approach has proven to be highly effective in controlling virus diseases in other crops.